TECHNICAL BULLETIN No. 256 AUGUST, 1931

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UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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## INTRODUCTION

The considerable areas supporting brush vegetation of various types that are found throughout the mountainous portions of northern Utah, eastern Idaho, and western Wyoming, on sites that would normally be expected to support western yellow pine forests, present to the forester many interesting problems. These areas form, in the main, a belt running from the Gulf of California to west-central Montana. The center of this belt is indicated by a broken line in Figure 1. Because of the unusual adaptability shown by western yellow pine in its wide latitudinal and altitudinal distribution, such a gap in the center of its natural range is difficult to explain. These areas of brush lie immediately below the Douglas fir type, at altitudes that elsewhere would be the natural habitat of western yellow pine.

This situation raises several questions. Has some element of climate or soil eliminated pine growth? Is the absence of pine accidental or due to some ascertainable influence? Can such influence, if it exists, be compensated or removed? The answer to these questions might point to the possibility of transforming these brush lands to pine forests, and such a transformation would obviously be highly desirable.

From 1910 to 1915 an earnest attempt was made, without previous technical investigation, to effect an improvement in cover by planting. High mortality of the planted stock followed. The question was thereby raised, whether the entire brush zone was possibly un-

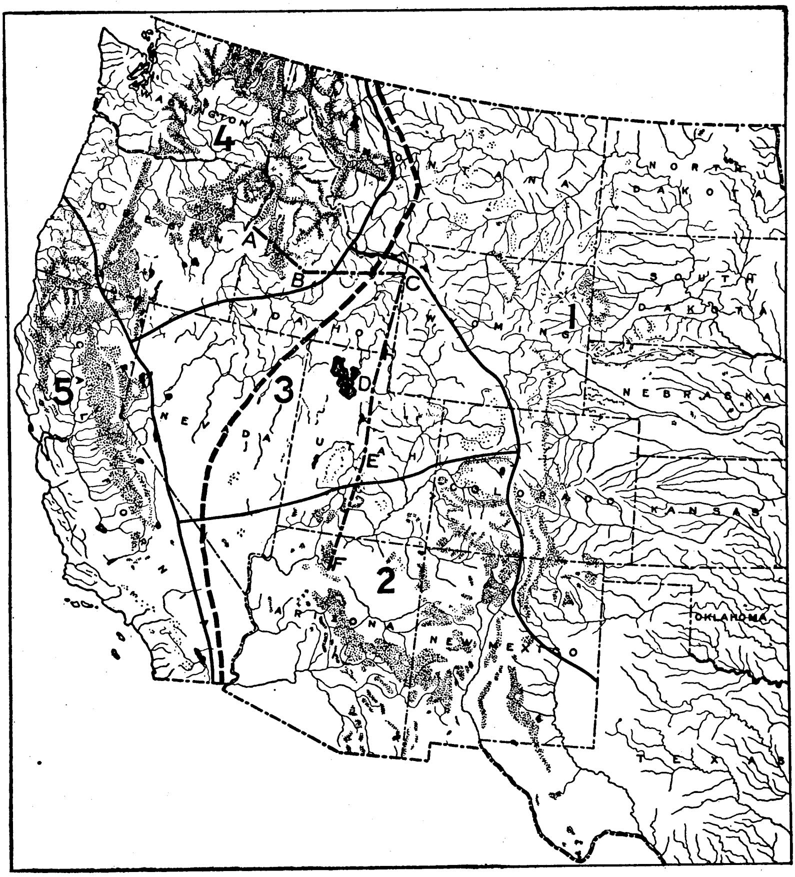


FIGURE 1.—Map of the western United States showing the distribution of western yellow pine and the following rainfall types: (1) Eastern Rocky Mountain; (2) south plateau; (3) central plateau; (4) north plateau; and (5) south Pacific. The stippled areas to the west of the heavy broken line represent the Pacific slope form (*Pinus ponderosa* Laws.), and those to the east of it represent the Rocky Mountain form (*P. ponderosa scopulorum* Engelm, or *P. scopulorum* (Engelm.) Lemmon.) (The authors are indebted to G. A. Pearson, E. N. Munns, and J. A. Larsen for data used in the preparation of this map.)

suitable for western yellow pine, despite the resemblance of these sites to those typical of the species in other regions. Planting operations were suspended until a definite answer to this question could be determined by special investigation. It was hoped that these investigations—of which the results are reported here—would not only settle the question of the possibility of western yellow pine establishment but would also result in the discovery of means by which areas suitable for western yellow pine could be detected and identified.

The investigations embraced three related lines of study. It was necessary first to determine the characteristics of climate and soil that occur within the pineless region and to compare these with the conditions prevailing where western yellow pine is found growing naturally. The second line of study was an actual test of western yellow pine transplants planted under different conditions in the brush-land areas. This test afforded a practical demonstration of the effects of the different factors upon the survival and thrift of the pine.

Finally, after it had been found that the established shrubby vegetation, by reducing the moisture supply, had a critical bearing upon the success of these plantations and that some of the brush-land species apparently resembled the pine in their response to the environmental conditions, additional studies of the natural succession of the native shrubs, their root development, and their leaf character were made to determine whether these species could be used as indicators of desirable planting sites for western yellow pine.

## NATURAL RANGE AND OCCURRENCE OF WESTERN YELLOW PINE

Western yellow pine is widely distributed throughout the Rocky Mountain region of the western United States, extending from the Canadian border to the Mexican line and from the bluffs bordering the rivers of western Nebraska to the Pacific coast in northern California. (Fig. 1.) Through the center of this region extends the brush-land belt already described. This belt can hardly be attributed to chance distribution, for it is far too extensive, and also there are certain differences in the silvical and taxonomic characters of the species on the two sides of the belt, indicating a separation of long standing. The silvical differences mentioned have recently been summarized by Korstian (*27*)[1] and will not be repeated here. The exact taxonomic relationship of the two forms is still in question. Some authorities consider them distinct species; others regard the southeastern form as a variety of the northwestern; still others hold that they are merely two climatic forms of the same species. In this bulletin the Pacific coast form will be referred to as *Pinus ponderosa* and the Rocky Mountain as *P. scopulorum*, simply as a concise means of reference.

In Montana the gap between the two forms is narrow and can not be located definitely, as outlying sporadic occurrences of both forms are frequent, but through Idaho, Utah, and western Wyoming the belt in which western yellow pine is absent is several hundred miles in width. The ponderosa form (fig. 2) extends southward and eastward in Idaho to the north fork of Salmon River and the head of the south fork of Boise River where the western yellow pine type ends suddenly. The scopulorum form is found in extensive stands as far north in Utah as the region around Panguitch and Widtsoe. (Fig. 3.) Beyond this point a narrow fringe of the type extends

[1] Italic numbers in parentheses refer to Literature Cited, p. 80.

along the east rim of Fishlake Plateau and even north to the Wasatch Plateau near Emery. Extensive bodies are found again in the Uinta Mountains. These are apparently an extension from the Colorado region, since the yellow pine is more widespread toward the east end of the range. A link of scattered botanical occurrences loosely connects this body with that in southern Utah, as the species is found skirting the southern edge of the Uinta Mountains to the Provo River drainage, while isolated groups exist in Big Cottonwood Canyon (pl. 1, A) and near the head of Parleys Canyon east of Salt Lake City. Thence it extends southward in a series of sporadic occurrences on both flanks of the Wasatch Range and Plateau to the extensive bodies of southern Utah. These small scattered extensions of western yellow pine usually occur either upon sandy soils or near streams where soil moisture conditions are exceptionally good. The trees are normal in appearance but are unable to reproduce aggressively enough to develop a type. In Nevada where the Rocky Mountain form reaches its westernmost occurrence it is also restricted to open, porous slope soils.

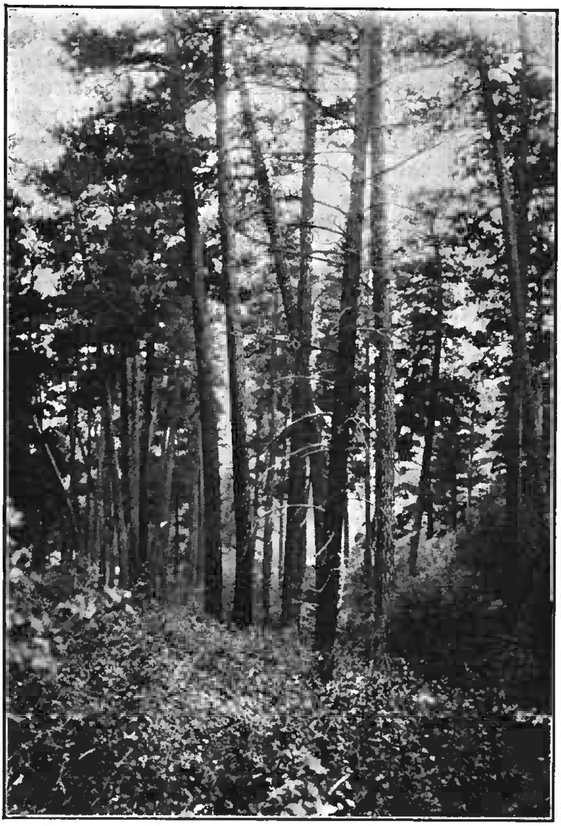

FIGURE 2.—A typical stand, of good quality, of the Pacific coast form of western yellow pine. (Salmon National Forest, Idaho)

Throughout its entire natural range, this species occupies the lower mountain slopes. South and east of the pineless belt, except in Wyoming, the Dakotas, and northern Colorado, a piñon-juniper type (*Pinus edulis*, *P. monophylla*, *Juniperus utahensis*, and *J. monosperma*) lies immediately below the western yellow pine type. To the north and west the yellow pine is the lowest conifer type, bordering the open grasslands or sagebrush areas, except on the Pacific slope, where it lies above an open woodland type of oak and digger pine (*P. sabiniana*). Above the western yellow pine lies a belt characterized by Douglas fir (*Pseudotsuga taxifolia*), although in many places fires have caused its temporary or partial replacement by lodgepole pine (*Pinus contorta*) or aspen (*Populus tremuloides aurea*). It also may be mixed with other species, particularly the true firs (Abies).

FIGURE 3.—Typical stand of the Rocky Mountain form of western yellow pine in southern Utah

The altitudinal relations of the various types along a belt extending from the bodies of western yellow pine in Idaho through the brush lands to the western yellow pine type in southern Utah (line ABCDEF in fig. 1) is shown in Figure 4. This section passes

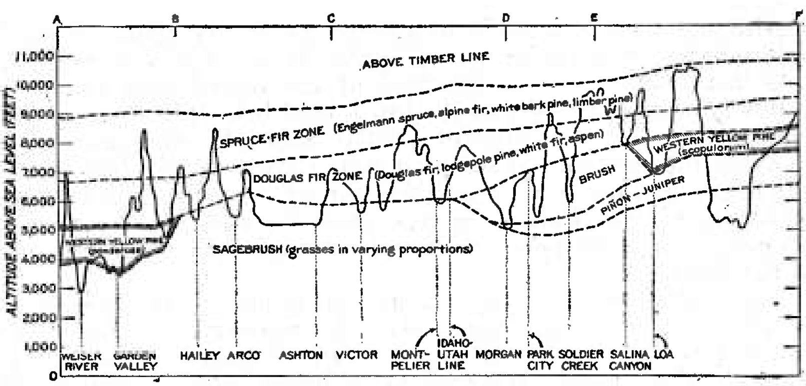


FIGURE 4.—Vertical section cut on line ABCDEF in Figure 1, showing topography and relationship of vegetational types along the section

through the middle of the region covered by this study and shows graphically how the western yellow pine is replaced in its logical altitudinal zone below the Douglas fir by sagebrush and associated plants in the region from near Hailey, Idaho, to the Utah-Idaho State line and by other brush vegetation from there south to the vicinity of Salina Canyon and Loa, Utah.

## TEMPERATURE, MOISTURE, AND SOIL IN THE WESTERN YELLOW PINE TYPE AND BRUSH LANDS

The possibility of introducing western yellow pine into the brush lands of the so-called pineless belt depends largely upon the prevailing local conditions of climate and soil. Of these, certain ecological factors can be changed or circumvented by planting, but others are insuperable. If the climate is fundamentally unsuited to its growth, forests of this species can not be established; but biotic factors, fire, or even minor climatic factors need not be regarded as insuperable obstacles. A knowledge of the various conditions within the brush lands and the surrounding pine lands, therefore, becomes of primary importance.

It is possible, however, to study the climate of the western yellow pine type and the intervening brush lands in only a general way, for little material is available except United States Weather Bureau cooperative station records consisting mainly of monthly averages. A number of stations are located in the western yellow pine type, but there are very few in the corresponding brush lands. Where a relation between altitude and the climatic factors can be determined with any degree of certainty, it is possible to use the more numerous valley stations below the western yellow pine and brush-land types as indicative of conditions occurring at somewhat higher elevations. The interpretation of the climatic and soil differences in terms of survival and growth of western yellow pine has been facilitated by studies by Bates (*5*, *6*, *7*) in Colorado and by Pearson (*36*, *37*, *38*) in Arizona.

### TEMPERATURE

Although temperature is recognized as a very potent factor in determining the distribution of species in mountainous regions, it does not explain the peculiarities of the distribution of western yellow pine on both sides of the brush-land belt. The mean monthly temperatures for a number of United States Weather Bureau stations in the western yellow pine belt, shown by rainfall types in Figure 5, indicate a very uniform set of conditions, especially in midsummer. The California type alone diverges notably from the average, having temperatures somewhat higher than the remainder of the region.

The weather records of valley stations in or near the pineless belt indicate a climate that approaches the warmer limit for western yellow pine as observed at various places within the range of this species. There must therefore be a broad zone extending from the base of the near-by mountains to intermediate elevations in which temperatures alone are not the limiting factor. An indication of the width of this zone is afforded in Table 1, which gives the altitudes and midsummer (July) temperatures of the valley stations, together with the indicated altitudes corresponding to a July mean temperature of 57.6° F. when a temperature gradient of

3.3° F. per 1,000 feet is applied to the base station. July temperatures were chosen as a basis because, as shown in Figure 5, they are more uniform throughout the western yellow pine zone than are the annual temperatures. The temperature of 57.6° F. was chosen as the lowest mean July temperature for western yellow pine, as this is the July mean for Elizabethtown, N. Mex., the coldest Weather

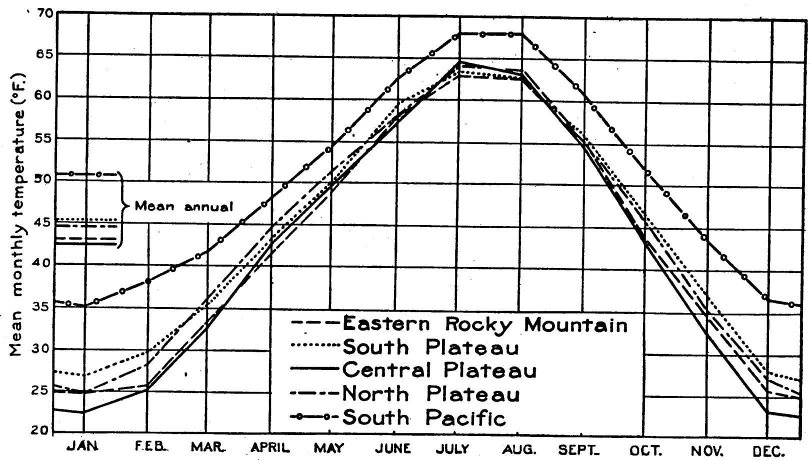


FIGURE 5.—March of mean monthly temperature for each rainfall type within the range of western yellow pine

Bureau cooperative station in the western yellow pine type. (Note also that Crescent, Oreg., has a July mean of 57.6° F.)

TABLE 1.—*Indicated upper altitudinal limits of western yellow pine in the pineless belt and adjacent territory, corresponding to the observed lowest mean July temperature (57.6° F.) for western yellow pine at Elizabethtown, N. Mex.*

| Station | Elevation | July normal temperature | Indicated upper limit | Actual upper limit [1] | Type at indicated upper limit |
|---|---|---|---|---|---|
| Idaho: | *Feet* | *°F.* | *Feet* | *Feet* | |
| Idaho City | 4,000 | 66.5 | 6,700 | 6,800 | Spruce-fir. |
| New Meadows | 3,860 | 62.5 | 5,400 | 5,500 | Pine-Douglas fir. |
| Ashton | 5,100 | 64.2 | 7,100 | | Lodgepole pine. |
| Blackfoot Dam | 6,200 | 61.9 | 7,500 | | Aspen. |
| Pocatello | 4,483 | 71.2 | 8,600 | | Lodgepole pine. |
| Oakley | 4,700 | 70.5 | 8,600 | | Alpine fir. |
| Wyoming: | | | | | |
| Afton | 6,250 | 61.1 | 7,300 | | Lodgepole pine. |
| Evanston | 6,860 | 61.4 | 8,000 | | Do. |
| Centennial | 8,074 | 60.0 | 8,800 | | Do. |
| Chugwater | 5,282 | 65.6 | 7,700 | | Do. |
| Utah: | | | | | |
| Logan | 4,507 | 71.8 | 8,800 | | Douglas fir. |
| Ogden | 4,310 | 78.0 | 10,500 | | Spruce-fir. |
| Morgan | 5,080 | 66.6 | 7,800 | | Douglas fir. |
| Manti | 5,575 | 69.2 | 9,100 | | Do. |
| Henefer | 5,301 | 64.9 | 7,500 | | Do. |
| Emery | 6,260 | 65.3 | 8,600 | 8,200 | Do. |
| Escalante | 5,700 | 69.2 | 9,200 | 9,000 | Do. |
| Ranch | 6,700 | 61.9 | 9,000 | 9,000 | Do. |
| Monticello | 7,050 | 66.0 | 9,600 | 8,500 | Do. |
| Park City | 7,000 | 61.2 | 8,100 | 7,000 | Do. |

[1] Where western yellow pine is present.

Table 1 indicates that, as a rule, favorable temperatures exist over an altitudinal belt from 1,000 to 4,000 feet in width in the region under discussion. It is evident, however, that July temperatures are not indicative of any certain type, for in the pineless region at elevations having approximately the same temperature as Elizabethtown, it is the rule to find Douglas fir or other forest types characteristic of higher altitudes.

It is realized that mean temperature alone may not be particularly significant. Maximum and minimum temperatures and the diurnal range in temperature frequently play an important rôle not revealed by mean temperatures. Such extremes are often of local occurrence, however, and depend largely upon local physiographic conditions, particularly as they affect air drainage. It is inconceivable that such extremes should occur generally throughout the various mountains of the pineless belt and yet disappear both to the north and the south in the continuation of the same mountain ranges.

Moreover, investigations of Bates and Roeser (*7*) have shown that western yellow pine is not greatly affected by high air temperatures or by the heat at the surface of the soil caused by direct insolation, and that it is, indeed, much more resistant to injury in this respect than any of its associates. The seed is larger and the young seedling is sturdier and appears to have thicker tissues more able to withstand heat than the conifers characteristic of the higher altitudes. Pearson (*36*), working in Arizona, came to the conclusion that western yellow pine is not limited at lower altitudes by high temperature but by moisture deficiency, since the species is successfully cultivated at points far below its natural range.

Western yellow pine is, however, markedly sensitive to temperature deficiencies and its upper altitudinal limit, occurring relatively low in the mountains, is undoubtedly determined in a measure by temperature deficiency. How this factor operates has not been determined thus far. Western yellow pine is notably resistant to sudden extremes. Growth is apparently not limited by occasional extremely low temperatures or by early or late frosts, but more likely by a deficiency of temperature during the entire growing season. Bates (*5*) has pointed out that western yellow pine ordinarily transpires fairly large quantities of water and suggests that in order to maintain a suitable temperature of the leaves it needs a hot situation to counteract the cooling caused by rapid evaporation from the leaf surfaces.

Mean temperatures in the zone immediately below the Douglas fir in the pineless belt differ only slightly from those of corresponding altitudinal zones in which the pine occurs. High temperatures, the heating effect of direct insolation, and unseasonable low temperatures and frost can not account for the absence of western yellow pine in the brush lands, since this species is notably insensitive to these conditions, which moreover are dependent mainly upon minor physiographic features and are rarely effective over large contiguous areas. It is evident, therefore, that temperature itself has no direct influence in determining the general absence of western yellow pine from the brush lands of the intermountain region and that other factors, such as those which influence the water relations of the plant, must be more important.

## MOISTURE

### EVAPORATION

In the semiarid intermountain region, where the moisture relations of the plant are very important, the rate of water loss from the leaves through transpiration is vital. This loss from evaporation can not, however, be studied in detail, as data are meager and have been collected only in a few widely scattered localities. Table 2 presents such records as are available.

TABLE 2.—*Mean daily evaporation from Livingston porous-cup atmometers at several stations within the range of western yellow pine and at the oaks station in central Utah*

| Station | April | May | June | July | August | September | October | November |
|---|---|---|---|---|---|---|---|---|
| Idaho: | | | | | | | | |
| Priest River, southwestern aspect, 1917 [1] | *C. c.* | *C. c.* | *C. c.* | *C. c.* | *C. c.* 31.0 | *C. c.* 17.2 | *C. c.* | *C. c.* |
| Near Viola [2] | | 12.3 | 7.4 | 11.2 | 15.6 | | | |
| Washington: Near Colfax [2] | | 7.0 | 7.0 | 10.6 | 17.0 | | | |
| California: | | | | | | | | |
| Quincy, 1916 [3]— | | | | | | | | |
| Southern aspect | | | | | 40.5 | 31.2 | | |
| Northern aspect | | | | | 28.2 | 21.7 | | |
| Average | | | | | 34.4 | 26.4 | | |
| Seven Oaks, 1916 [4] | 30.9 | 37.0 | 51.2 | 48.9 | 52.1 | 50.8 | 37.3 | 42.1 |
| Arizona: Flagstaff, 1916 [5] | | | | 26.4 | 19.1 | 19.0 | | |
| Utah [6] (central): | | | | | | | | |
| Oaks station, 1915 | | | [7] 39.0 | 35.4 | 40.7 | 19.9 | | |
| Oaks station, 1916 | | | [8] 48.5 | 41.2 | 39.9 | [9] 55.1 | | |
| Average | | | 43.8 | 38.3 | 40.3 | 37.5 | | |

[1] Data supplied from Priest River Experimental Forest by J. A. Larsen.
[2] Data obtained by J. E. Weaver (*53*).
[3] Data from Feather River branch of the California Forest Experiment Station by E. N. Munns.
[4] Data supplied by E. N. Munns from a former field station of the Forest Service near Seven Oaks (Redlands), Calif.
[5] Data supplied by G. A. Pearson from Fort Valley branch of the Southwestern Forest and Range Experiment Station.
[6] At Great Basin branch of Intermountain Forest and Range Experiment Station.
[7] Mean of last 10 days.
[8] Mean of last 20 days.
[9] Mean of first 6 days.

Evaporation is high at the oaks station in Utah but not so high as at Seven Oaks, near Redlands, at the lower edge of the California western yellow pine belt, and scarcely more than the average at Quincy in the same State. In Arizona, farther south, the evaporation is much more moderate. When these figures are compared with precipitation for the same months at the same stations, it becomes apparent that rainfall has played a large part in determining the degree of evaporation. The California western yellow pine belt has very dry summers, whereas July and August in Arizona are normally rainy. Conditions in Utah are intermediate. The persistence of rainy weather has apparently affected the total monthly evaporation so much that the influence of other factors is obscured. Also Table 2 does not indicate the intensity of evaporation when it increases to significant proportions during hot dry periods in each region.

The figures obtained by Weaver in Idaho and Washington appear considerably lower than the records of precipitation in that region would lead one to expect. Weaver (*53*), in commenting upon these figures, contends that it is the relatively low evaporation rate, which persists even during clear hot periods marked by scant precipitation, together with the high water-holding capacity of the soil, which makes it possible for western yellow pine to grow in eastern Washington and adjacent Idaho.

Although the sensitiveness of western yellow pine to evaporation is little known, and the effect of evaporation as such can not be evaluated in a wholly satisfactory manner, yet evaporation must be regarded as an ever-present factor which may sometimes be very effective. All through the following discussion of precipitation, evaporation is considered by implication, since periods of heavy precipitation are usually marked by low evaporation and evaporation and transpiration are highest during periods of drought.

### MEAN ANNUAL PRECIPITATION

Table 3 shows the low total of precipitation which is sufficient for western yellow pine. All through Colorado, for example, this species exists where the annual precipitation is as low as 16 inches. Precipitation is obviously not the controlling factor in the present problem, since the annual total is fully as heavy on the lower mountain slopes in the pineless belt as in many parts of the western yellow pine region. In the valleys of the pineless region are many stations with annual precipitation as heavy as that which occurs at western yellow pine stations in Montana and Colorado. Above these valley stations, in the wide belt of favorable temperatures already mentioned, the precipitation is even greater than in the valleys. Alter (*1*) figures the average annual rainfall gradient on windward slopes in this region as about 4 inches for each 1,000 feet of rise. Since favorable temperatures usually extend at least 2,000 feet above the valley stations it is evident that a considerable increase in rainfall is assured in the zone which appears to be potentially suited to western yellow pine. About 20 to 24 inches of precipitation a year, an amount comparable with that in the western yellow pine region except on the west slope of the Sierras in California, should be expected.

TABLE 3.—*Mean annual precipitation at United States Weather Bureau stations within the western yellow pine type*[1]

| Location | Mean annual precipitation | Location | Mean annual precipitation | Location | Mean annual precipitation |
|---|---|---|---|---|---|
| Washington: | *Inches* | Utah: | *Inches* | Colorado: | *Inches* |
| Goldendale | 16.20 | Alton | 23.64 | Georgetown | 14.97 |
| Cle Elum | 24.47 | Ranch | 24.63 | Cheeseman | 16.58 |
| Spokane | 18.85 | Average | 24.14 | Durango | 16.67 |
| Colville | 17.62 | Idaho:[2] | | Idaho Springs | 16.39 |
| Average | 19.28 | Boulder Mine | 31.49 | Westcliffe | 15.18 |
| Oregon: | | Garden Valley | 26.67 | Average | 15.96 |
| Crescent | 20.14 | Grimes Pass | 27.55 | New Mexico: | |
| Blue Mountain saw-mill | 41.07 | Idaho City | 21.17 | Cloudcroft | 23.46 |
| Chiloquin | 19.48 | McCall | 26.86 | Gallinas | 25.25 |
| La Grande | 18.05 | New Meadows | 23.00 | Mineral Hill | 22.72 |
| Wallowa | 18.80 | Coeur d'Alene | 23.90 | Elizabethtown | 18.73 |
| Average | 23.51 | Average | 25.81 | Rociada | 22.45 |
| California: | | Montana: | | Average | 22.52 |
| Truckee | 26.93 | Missoula | 15.73 | Arizona: | |
| Blue Canyon | 69.94 | Kalispell | 16.94 | Flagstaff | 22.81 |
| Yosemite | 37.43 | Ekalaka | 13.22 | Williams | 22.13 |
| Nevada City | 54.35 | St. Ignatius | 16.23 | Fort Valley | 21.52 |
| Weaverville | 39.03 | Average | 15.53 | Grand Canyon | 17.55 |
| Average | 45.54 | Wyoming: | | Average | 21.00 |
| | | Centennial | 18.49 | | |
| | | Chugwater | 15.43 | | |
| | | Average | 16.96 | | |

[1] From Climatological Data, 1919, U. S. Dept. Agr., Weather Bur., except as specified.
[2] Idaho records were specially compiled.

In the pineless region there is unfortunately only one station, Park City, located directly in the brush-land belt. Rainfall records at this station and at representative valley stations below the brush belt in this region are shown in Table 4. Omitting Park City, the average annual rainfall is 16.25 inches. Here is further evidence that deficiency in total precipitation is not the factor which limits the distribution of western yellow pine in the intermountain region.

TABLE 4.—*Mean annual precipitation at stations in pineless region of Utah* [1]

| Station | Elevation | Mean annual precipitation | Station | Elevation | Mean annual precipitation |
|---|---|---|---|---|---|
| | *Feet* | *Inches* | | *Feet* | *Inches* |
| Government Creek | 5,277 | 13.60 | Moroni | 6,000 | 16.14 |
| Spanish Fork | 4,711 | 17.40 | Ogden | 4,310 | 15.02 |
| Laketown | 6,200 | 15.19 | Salt Lake City | 4,408 | 16.03 |
| Logan | 4,507 | 16.40 | Park City | 7,000 | [2] 20.57 |
| Morgan | 5,080 | 20.23 | | | |

[1] From Climatological Data, Utah, 1919, U. S. Dept. Agr., Weather Bur., except as specified.
[2] Specially compiled.

### SEASONAL DISTRIBUTION OF PRECIPITATION

The great variation in annual precipitation found in the western yellow pine type in different States (the range is from 15.53 inches in Montana, where the heaviest rainfall occurs in the summer, to 45.54 inches in California, where the summers are dry) suggests that differences in forest growth may be caused rather by the seasonal distribution of precipitation throughout the year than by total rainfall.

The irregularity in the distribution of precipitation throughout the year in the western part of the United States has been noted by many meteorologists. Ward (*50*) has divided the United States into a number of rainfall provinces, each having a typical form of rainfall distribution. This classification has proved very useful in the present study, although it has been necessary to modify Ward's rainfall provinces to show clearly the characteristics of the transition type in the central pineless belt.

The outstanding characteristics of the rainfall provinces are shown in Figure 6, which represents average conditions at stations within the western yellow pine type or its brush-land equivalent. In the north plateau province precipitation is fairly heavy in winter. It decreases slowly through April but in May rises above 2 inches at points within the western yellow pine belt. From May it drops slowly to a minimum in August, after which it rises again. From May on, it conforms to the Pacific coast type of rainfall, except that the differences between summer and winter are much less marked. In May alone do the characteristics of the eastern Rocky Mountain rainfall type prevail, good rains in that month being typical throughout the country east of the plateau region.

The south plateau type of rainfall, on the other hand, is somewhat similar to the south Pacific type until July. Rainfall decreases through the spring months to a minimum in May and June, which season is known throughout the Southwest as the arid foresummer.

In July a sharp rise in precipitation occurs. This is maintained through August, and the curves conform closely to that of the eastern Rocky Mountain region during these months and until November.

In the central plateau region rainfall in May, the first month of the growing season, is intermediate between that in the north plateau western yellow pine region and that to the south. In June this region becomes practically as dry as the south plateau region, but in July, instead of the sharp increase characteristic of the south, only

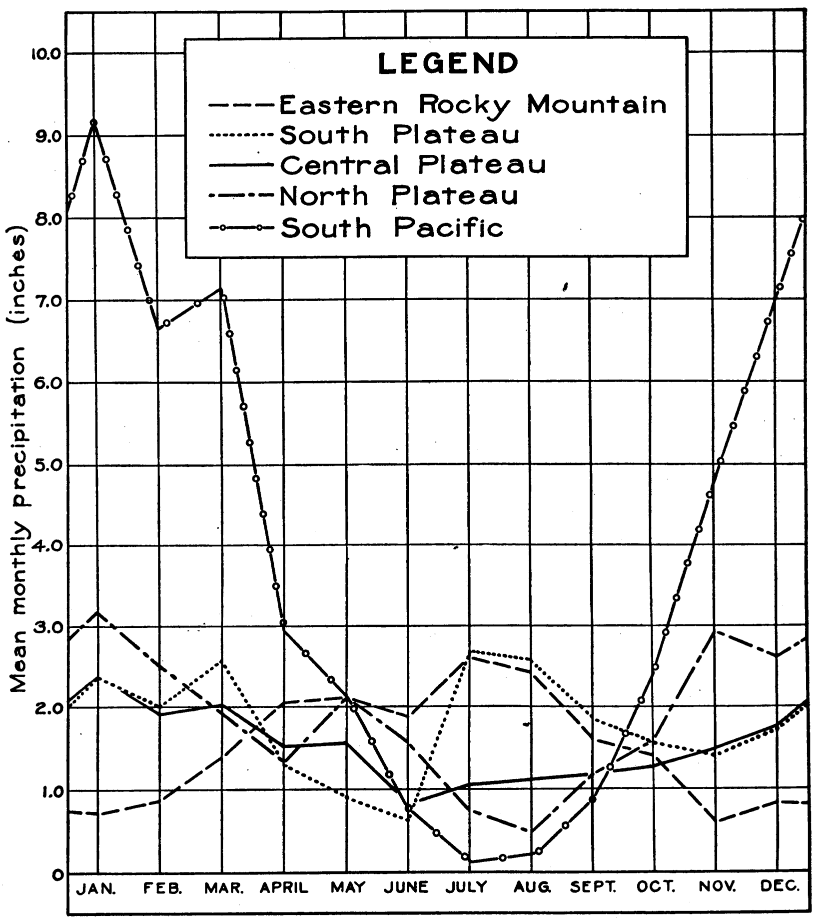


FIGURE 6.—March of mean monthly precipitation for each rainfall type within the range of western yellow pine. (Compiled from U. S. Weather Bureau records)

a slight rise is shown in the curve. In August, the last effective month of the growing season, conditions are but little better. The region has neither the favorable rainfall characteristic of May in the north nor the favorable conditions common in July and August in the south.

Not only does the total rainfall for May for the central plateau region show a notable decrease over that for the north plateau, but also its distribution within the month changes. A study of conditions at a number of Weather Bureau stations for which mean daily precipitation records are available shows that well within the northwestern yellow pine zone, at Spokane, Wash., the crest of the spring maximum occurs on June 16, after which the rainfall drops gradually to the summer minimum on August 10. Farther south, at Baker City, Oreg., the crest of the spring rainfall culminates on May 27; at Boise, Idaho, still nearer the brush lands, it culminates on June 3; at Pocatello, Idaho, well within the brush-land region, on May 24; and at Salt Lake City, Utah, on May 2. Furthermore, the driest part of the summer in a similar manner occurs progressively earlier—at Spokane on August 10, at Baker City on July 22, at Boise on July 10, and at both Pocatello and Salt Lake City on June 25. The early May precipitation in the western yellow pine zone often falls as snow, and the accompanying cold weather is not conducive to rapid or complete germination of western yellow pine. Furthermore, the long, hot, cloudless days of June follow closely this period of cold precipitation. Both conditions serve notably to intensify the unfavorable situation brought about by the natural deficiency in the May precipitation throughout the central-plateau region.

The nature of this transition through the central plateau region will be clearly evident from a comparative study of Figure 7, which shows rainfall distribution during the four months of the growing season in the central plateau region, and Figure 1, which gives the range of western yellow pine in the intermountain region. May rainfall in excess of 2 inches is found in the western yellow pine type in the plateau region of southwestern Idaho. To the east and south there is a very rapid decrease in the precipitation during that month. June is dry throughout the entire region; the heaviest rainfall occurs in central Idaho and northern Wyoming on the edge of the Montana region, where there is normally ample precipitation throughout the month. In July the situation is reversed. The heaviest rainfall (about 3 inches) occurs in the extreme southern part of the region in the mixed yellow pine and Douglas fir forest on the higher parts of the Kaibab Plateau in northern Arizona. A belt of suitable July rainfall extends northward through the higher mountains of central Utah into the ranges of western Wyoming, but at altitudes too high for the pine. In August, similar conditions obtain, with the heaviest precipitation again occurring in the southern part of the region. The central Idaho plateau is marked by extremely low precipitation.

The significance of the seasonal distribution of rainfall as it relates to the occurrence of the western yellow pine type is brought out even more forcibly in Figure 8, which shows the altitudinal relationships of the forest types and precipitation along the section illustrated in Figure 4.

The western yellow pine type stops abruptly in Idaho where the May rainfall suddenly drops below 2 inches in the proper altitudinal belt below the Douglas fir zone. This coincides with the leeward slopes of the Sawtooth Range and other near-by uplifts. Similarly, in southern Utah the type fails to extend northward beyond the point where the rainfall for July and August falls below a critical amount (about 1.5 inches) in the altitudinal zone suited to its temperature requirements. Only in the region of northwestern Wyoming and adjacent Idaho (in the vicinity of point C, fig. 1) is western yellow

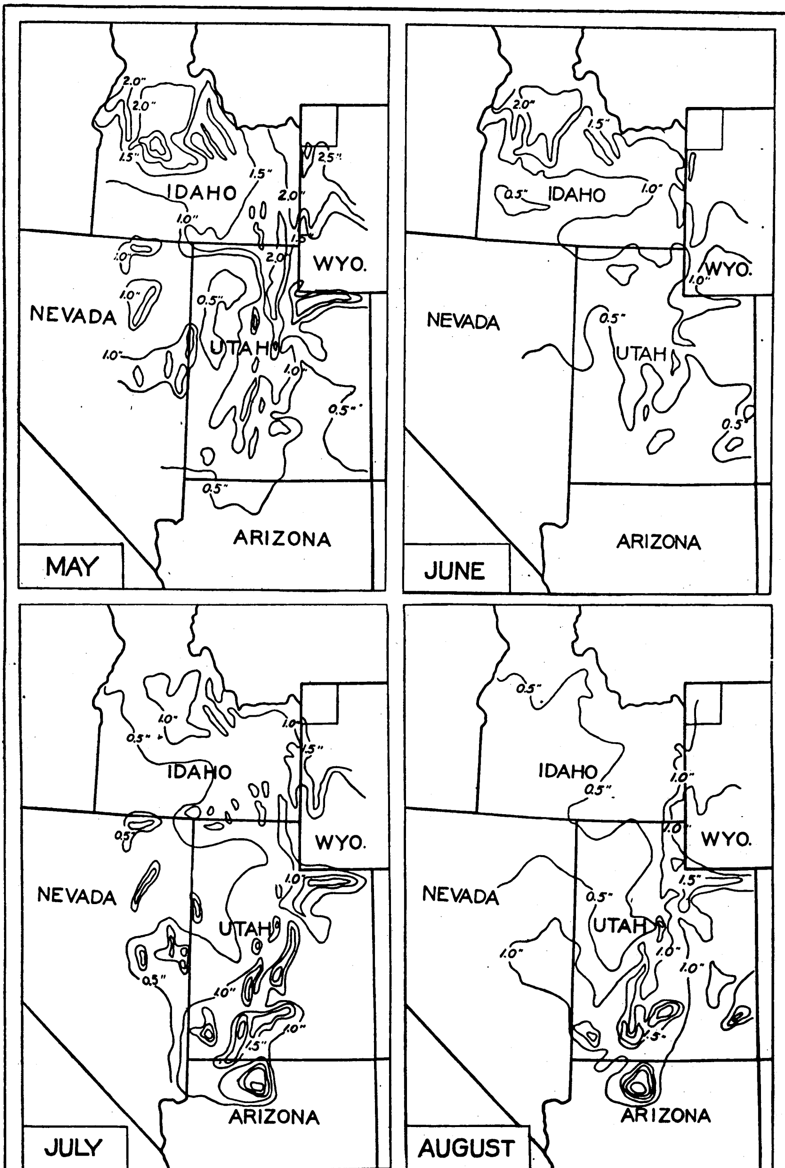


FIGURE 7.—Geographical distribution of mean monthly precipitation in the central plateau region during the four months of the growing season. (Compiled from U. S. Weather Bureau records)

pine absent from a region in which the precipitation is apparently favorable. Here many conditions in the upper sagebrush type are virtually similar to those in the pine type farther west. In June the conditions are very similar; also no significant differences are apparent in July or August. Other factors must therefore be sought to explain the absence of western yellow pine in this locality.

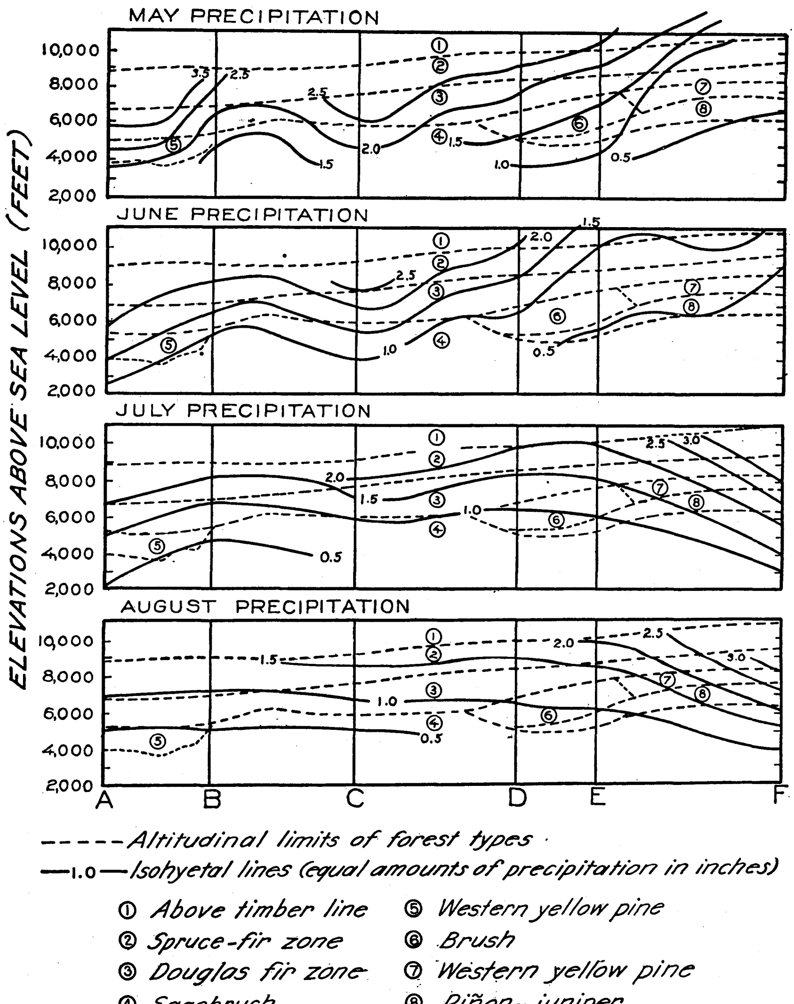


FIGURE 8.—Altitudinal relationships of vegetational types and precipitation during the four summer months over the sections ABCDEF shown in Figures 1 and 4

The fact that the rainfall during the months of May, June, July, and August in the California western yellow pine zone is lower than in these brush lands can not be cited in refutation of the facts brought out here. The spring temperatures in the western yellow pine type on the west slope of the Sierras in California, as shown in Figure 5, are notably higher than elsewhere, and accordingly the heavy April rainfall must play an important part in the reproduction of western yellow pine in that region. Thus the short critical period between germination and establishment of deep-feeding rootlets is evidently passed under favorable conditions.

### SOIL MOISTURE

The influence of rainfall is undoubtedly exerted chiefly through the moisture available in the upper soil layers at the time of germination and early growth of the seedlings. The extent to which such variations in rainfall as are here involved actually influence soil moisture has never been fully investigated. A comparison between a station in the typical western yellow pine type of Arizona and another in the oak brush of central Utah reveals significant differences in available moisture within the upper foot of soil, attributable to differences in rainfall distribution during the summer months. Figure 9 shows the trend of soil moisture at these two stations.[2]

Like precipitation, average soil moisture can be determined only after many years' records have been obtained. The curves in Figure 9 may therefore be open to criticism. These, however, may be sup-

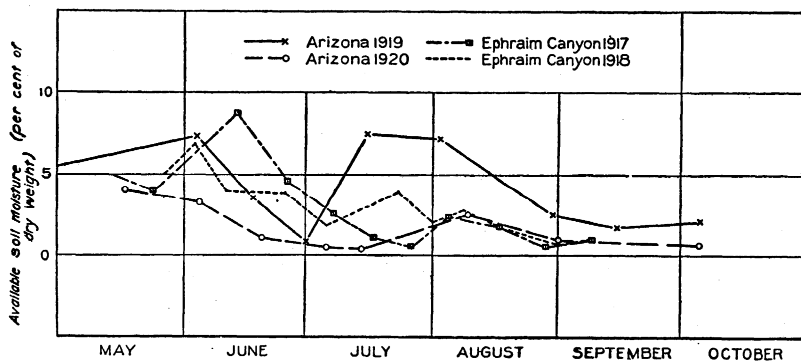


FIGURE 9.—March of soil moisture in northern Arizona and central Utah

plemented, to a certain extent at least, by a study of the rainfall records. At the Fort Valley branch of the Southwestern Forest and Range Experiment Station the rainfall for May, June, July, and August, 1919, was 77 per cent in excess of the normal for these four months, and for the same period in 1920 it was 39 per cent below the normal. The excess for one year and the deficiency for the next were fairly well distributed throughout the entire period. In Ephraim Canyon at Manti, a valley station approximately 6 miles distant from the point where the Utah soil-moisture studies were made, the rainfall was approximately 60 per cent above normal in 1917, the year being marked by exceptionally heavy May rainfall. In 1918 it was 12 per cent above normal, most of the excess coming in July, which had approximately three times the usual fall. Both

[2] The Arizona curves of Figure 9 represent the march of available soil moisture at a depth of 6 inches under western yellow pine cover at the Fort Valley branch of the Southwestern Forest and Range Experiment Station (37, figs. 4 and 6), the curve for 1919 being taken from Figure 4 and the curve for 1920 from Figure 6 (based on the curve derived from soil samples taken on the west side of the trees). The Utah curves are based on the average of two sets of determinations, one at a depth of 0 to 6 inches, and the other at 6 to 12 inches, both under oak-brush cover near the Great Basin branch of the Intermountain Forest and Range Experiment Station in Ephraim Canyon, Manti National Forest.

Utah curves are therefore high, whereas one Arizona curve is high and the other low. The higher Utah curve and the higher Arizona curve are comparable.

These facts, considered in connection with the curves in Figure 6, show that although the brush lands have the greater amount of available soil moisture in the spring the summer rains are insufficient to compensate for the depletion due to evaporation and the demands of vegetation during the periods between storms. In Arizona, on the other hand, the rains are of sufficient intensity to bring about a notable increase of soil moisture, which holds throughout the remainder of the growing season. Western yellow pine seedlings resulting from germination in the early spring are notably short-lived in Arizona (*37*), and obviously their chances of survival are still less under the oak brush of central Utah. The chances of germination and growth during July and August, the main germination period in Arizona, are also decidedly minimized in Utah by the much lower soil moisture. While no similar comparisons of soil moisture are possible between brush sites and western yellow pine lands in Idaho, similar relationships doubtless exist. The accumulation of soil moisture in the winter seems to play little or no part, because the critical zone is in the upper soil layers, which dry out rapidly after the snow melts in the spring.

#### EFFECTS OF SURFACE AND SOIL MOISTURE ON SEEDLING ESTABLISHMENT

Experiments by Bates (*5*) have indicated that western yellow pine, though commonly considered as very drought resistant, uses a large amount of water under average conditions. However, Pearson's experiments (*38*), while confirming the water-using estimates, seem to prove that western yellow pine is very well adapted to the reduction of transpiration in time of drought. This faculty, added to the seedling's rapid development of taproot that reaches relatively great depths in a short time, seems to assure successful drought resistance once the seedling is well established. There is, nevertheless, a short but very critical period immediately following germination when abundant moisture in the upper soil layers is absolutely indispensable. It is thus evident that distribution of rainfall and such soil characteristics as relate to the corresponding moisture supply may be very important in defining the range and occurrence of western yellow pine.

The facts thus far considered strongly suggest that the distribution of western yellow pine in the intermountain region is determined chiefly by seasonal precipitation. This assumption is substantiated by conditions in western Idaho, where western yellow pine finds favorable temperatures, and rainfall in May is approximately 2 inches, or about the minimum required for the germination and early development of western yellow pine. The root systems of the newly germinated plants develop downward with great rapidity and become established before the advent of the dry period, which reaches its maximum intensity during the latter part of July and August. But on the leeward (east) side of the Sawtooth Range and adjacent uplifts, May precipitation in the zone having temperatures suited to western yellow pine suddenly drops to less than 2 inches. Under these conditions western yellow pine is unable to germinate and develop a root system capable of supplying sufficient water for its existence.

The absence of western yellow pine in eastern Idaho and adjacent parts of Wyoming, where rainfall again becomes sufficient for its development in the zone immediately below the Douglas fir (figs. 7 and 8) must be explained by factors other than May precipitation alone. Here the extreme dryness in June characteristic of the great belt extending southward from the upper Snake River plains through Idaho and northern Utah is very trying, and, as already noted, where germination and early development of seedlings in early May have been hindered by the cold, these long, hot, dry days of June prove too severe for roots not sufficiently developed to reach the deeper soil moisture. This is invariably the history of western yellow pine seedlings which spring up in May from seed artificially sown in this region.

In the south plateau region May is normally dry and June exceedingly dry. Here very little spring germination of western yellow pine occurs, and none of the seedlings which occasionally start survive this dry period. In July, however, heavy rains begin and normally continue through August. Rapid germination follows during the warm weather, and roots are quickly developed and penetrate deeply, making it possible for the seedlings to maintain themselves. Farther north, more precipitation occurs in July and August than in June, but soil moisture here, as shown in Figure 9, remains notably inferior to that in the Southwest. The rains are less frequent and lighter, and the seedlings which spring up are unable to develop a taproot before the advent of a dry period which they are unable to withstand. The heaviest summer rains in the brush-land zone usually occur in August, whereas in Arizona July is somewhat wetter than August. Germination in the brush lands, therefore, occurs later and plants from artificially sown seed, although they are occasionally successful in surviving the dry periods between storms in August, are so young and tender that they invariably succumb to the frosts which usually occur during the first week in September. The distribution of rainfall through the summer, as well as the foresummer, thus plays a leading rôle in determining the range of western yellow pine.

## SOIL

Although rainfall distribution fixes the general limits of the western yellow pine lands, any closely defined boundary between these lands and the brush lands must be determined mainly through the study of soil conditions, since the critical factor, available soil moisture, may be greatly modified locally by soil character. Moreover, soil texture and structure may account not only for water-holding capacity and available soil moisture but also for the degree of aeration and penetrability both by soil moisture and by plant roots. With the object of determining the effect of soil conditions on the problem at hand, a number of samples of soil, both in the pineless belt and in the western yellow pine type, were submitted to the laboratory tests summarized in Table 5.

TABLE 5.—*Water-holding capacity, wilting coefficient, lime reaction, soluble humus content, hydrogen-ion concentration, origin, and classification of soils within the pineless belt and the western yellow pine type in Utah, Arizona, Colorado, and Idaho*

| Sample No. | Location | Plant association | Soil-forming material | Soil texture: Topsoil | Soil texture: Subsoil | Water-holding capacity | Wilting coefficient | Lime reaction with hydrochloric acid | Soluble humus [1] | H-ion concentration (pH) [2] |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cache National Forest, Idaho: | | | | | *Per cent* | *Per cent* | | *Per cent* | |
| 13 | Mink Creek | Sagebrush | Schist, diorite, porphyry, limestone, quartzite. | Dark-brown silt loam | Gray silty very fine sandy loam. | 52.6 | 11.8 | None | 2.14 | 7.8 |
| 5 | do | Purshia-symphoricarpos. | do | Brown silty very fine sandy loam. | Gray silt loam | 58.7 | 13.2 | do | 2.80 | 7.8 |
| 11 | do | Ceanothus-amelanchier. | do | do | do | 67.2 | 13.6 | do | 2.78 | 7.6 |
| 7 | do | Aspen | do | Gray silty very fine sandy loam. | do | 58.8 | 10.4 | do | 1.99 | 6.9 |
| | Wasatch National Forest, Utah: | | | | | | | | | |
| 91 | Beaver Creek, western aspect. | Oak brush | Quartzite, sandstone | Rocky silty fine sandy loam. | | 47.9 | 9.6 | do | 1.60 | 8.1 |
| 95 | Big Cottonwood Canyon, southern aspect. | Sage-ceanothus-oak-aspen. | Limestone, granodiorite, quartz diorite. | Rocky fine sandy loam. | | 54.5 | 12.4 | do | 2.64 | |
| 102 | Big Cottonwood Canyon, western aspect. | Ceanothus-oak | do | Light-brown gravelly fine sandy loam. | | 54.1 | 10.9 | do | 2.86 | 8.0 |
| | Uinta National Forest, Utah: | | | | | | | | | |
| 80 | Salt Creek | Sagebrush | Sandstone | Very fine sandy loam | | 43.5 | 8.2 | do | 1.44 | 8.0 |
| 81 | do | Oak brush | do | Brown fine sandy loam. | Gray silt loam | 55.4 | 12.0 | do | 3.24 | |
| | Manti National Forest, Utah: | | | | | | | | | |
| 61, 64 | Ephraim Canyon | Manzanita-squaw-apple. | Geological clay, sandstone. | Gray silty clay loam | Compact clay | 49.4 | 11.8 | Very strong | .24 | 8.5 |
| 65, 66 | do | Sage flat | Limestone, sandstone | Brown silty clay loam | Yellow stiff, waxy, calcareous clay. | 62.6 | 13.7 | Strong | 2.02 | 7.9 |
| 71, 72 | do | Oak brush | Geological clay | Brown clay loam | Yellow somewhat stony clay. | 62.4 | 15.7 | do | 3.62 | 8.2 |

[1] Determined by the Grandeau method of extraction with ammonia.
[2] Determined by E. F. Snyder, laboratory of soil-fertility investigations, Bureau of Chemistry and Soils, except as otherwise noted.

TABLE 5.—*Water-holding capacity, wilting coefficient, lime reaction, soluble humus content, hydrogen-ion concentration, origin, and classification of soils within the pineless belt and the western yellow pine type in Utah, Arizona, Colorado, and Idaho*—Continued

| Sample No. | Location | Plant association | Soil-forming material | Soil texture: Topsoil | Soil texture: Subsoil | Water-holding capacity | Wilting coefficient | Lime reaction with hydrochloric acid | Soluble humus | H-ion concentration (pH) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Manti National Forest, Utah—Continued. | | | | | *Per cent* | *Per cent* | | *Per cent* | |
| 43, 75, 76 | Lower Joes Valley | Western yellow pine | Limestone, sandstone | Gravelly very fine sandy loam. | Calcareous alluvium of bowlders, gravel, very fine sand, and silt. | 47.3 | | Moderate | 0.75 | 8.6 |
| 37 | The pines station | do | Sandstone | Brown loosely coherent fine sand. | Grayish-yellow fine sand. | 27.4 | 3.3 | None | .24 | 7.4 |
| | Fishlake National Forest, Utah: | | | | | | | | | |
| 16 | Mud Spring Hollow | Oak brush | do | Black silty very fine sandy loam. | | 55.1 | 10.9 | do | 4.40 | |
| | Fillmore National Forest, Utah: | | | | | | | | | |
| 26 | Beaver Canyon | Western yellow pine | Rhyolite porphyry, rhyolite, quartz-porphyry. | Brown silty and gravelly very fine sandy loam. | | 40.4 | 10.5 | do | 1.86 | 8.0 |
| | Powell National Forest, Utah: | | | | | | | | | |
| 17 | Lost Creek | Oak brush | Andesite and quartz-diorite porphyries, micaceous sandstone. | Brownish-gray very fine sandy loam. | | 44.7 | 9.1 | do | 2.30 | 8.1 |
| 18 | Escalante Creek | Western yellow pine | Limestone | Dark-gray gravelly loam (slightly sandy). | | 58.2 | 15.2 | Strong | .76 | |
| 19 | do | do | Calcite, sandstone conglomerate, quartz, trachite porphyry. | Gravelly to stony very sandy loam. | | 51.4 | 11.2 | do | .92 | 8.5 |
| 21 | Sweetwater Canyon | do | Limestone, sandstone conglomerate. | Brown silty very fine sandy loam (slightly gravelly). | | 35.5 | 7.2 | Very strong | .82 | 8.9 |
| | Sevier National Forest, Utah: | | | | | | | | | |
| 22 | Red Canyon | do | Limestone, sandstone | Reddish-brown gravelly very fine sandy loam. | | 53.6 | 14.1 | Strong | .26 | 8.3 |
| 23 | Daves Hollow | do | Limestone | Brown gravelly very fine sandy loam. | Gray gravelly very fine sandy loam. | 31.3 | 10.7 | Moderate | .04 | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Dixie National Forest, Utah: | | | | | | | | | |
| 25 | Pine Valley | do | Andesite | Brown slightly gravelly very fine sandy loam. | | 33.0 | 7.4 | Slight | 1.90 | 7.6 |
| | Kaibab National Forest, Ariz.: | | | | | | | | | |
| 24 | Jacob's Lake | do | Limestone conglomerate. | Black gravelly to stony fine sandy loam. | | 45.1 | 11.0 | None | 2.32 | 7.9 |
| | Coconino National Forest, Ariz.: | | | | | | | | | |
| 38 | South of Flagstaff | do | Arenaceous limestone | Very fine sandy loam (slightly silty) giving loamy texture. | | 48.4 | 6.5 | do | 2.08 | |
| 39 | do | do | do | Dark-brown silty clay loam. | Brown compact fine-grained clay. | 57.0 | | do | 2.12 | 8.3 |
| 40 | Fort Valley | do | Basalt | Dark reddish-brown rather friable clay. | Red sticky clay | 61.3 | 12.8 | do | 1.90 | [3] 7.0 |
| 44 | Northeast of Flagstaff. | do | Volcanic cinders | Mixture of cinders, fine sand, gravel, and silt. | Dark-brown friable clay. | 57.7 | 8.8 | do | | [3] 7.0 |
| | San Isabel National Forest, Colo.: | | | | | | | | | |
| 83, 86 | Oak Creek | do | Granite | Brown gravelly loam | Light-brown gravelly clay loam. | 36.0 | 7.9 | do | 1.28 | 8.5 |
| | Pike National Forest, Colo.: | | | | | | | | | |
| 87 | Deadmans Gulch | do | Sandstone | Reddish-brown loamy very fine sand. | | 39.9 | 6.0 | Slight | .24 | 9.1 |
| | Payette National Forest, Idaho: | | | | | | | | | |
| 41 | Carpentier and Poorman Creeks. | do | Granite | Gray gravelly loam | | 25.8 | 4.8 | None | .98 | [3] 8.0 |
| 88 | Big Pine Creek basin. | do | do | Brown gravelly loam | | 42.3 | 10.5 | do | 1.76 | [3] 7.7 |
| 90 | Big Pine Creek, southern aspect. | do | do | Gray gravelly loam | | 37.0 | 6.7 | do | 1.28 | |
| | Weiser National Forest, Idaho: | | | | | | | | | |
| 42 | Filley Creek | do | Basalt | Dark-brown gravelly silt loam. | | 70.0 | 16.1 | do | 3.03 | [3] 7.5 |
| | Nevada National Forest, Nev.: | | | | | | | | | |
| 45 | Snake Creek | do | Granite | Light-brown gravelly silt loam. | | 47.6 | | do | 1.94 | [3] 7.8 |

[3] Determined by Korstian, using the colorometric method developed by Wherry.

## COMPARISON OF WESTERN YELLOW PINE AND BRUSH-LAND SOILS

Light as well as heavy textured soils are found both in the western yellow pine region and in the brush-land belt. Nevertheless, those of heavy texture seem to be more common in the pineless area. These vary from silt loam to heavy compact waxy clay, and only occasionally does a loam or a sandy loam occur. A high lime content is prevalent. The open-textured and porous soils that are present in the pineless belt are found more commonly in the northern part of it.

No consistent differences in soil texture are reflected in the moisture-holding constants of the soils from the western yellow pine lands and brush lands, although there is a marked tendency for the wilting coefficient and water-holding capacity to be lower in the pineland soils than in those from the typical brush lands. Low wilting coefficients and water-holding capacities are correlated with light porous soils. Some of the heaviest soils supporting pine stands (as judged by the water-holding capacity) lie far within the western yellow pine zones where rainfall is very favorable, as in the case of sample No. 42, from the Weiser National Forest (Table 5) which has the highest water-holding capacity of all soils collected. Sample No. 40, the next highest of the heavy soils, comes from the pine region of Arizona, and other samples showing values nearly as high come from near the limits of the western yellow pine (samples Nos. 18, 19, and 22). It is notable, however, that one of the lightest soils (sample No. 37) comes from an outlying body of pine, well within the general brush-land region. That these points are more than mere coincidences is clear when the reaction of western yellow pine to soil texture is noted.

The soluble humus present in the soil, as determined by the Grandeau method (*20*) of extraction with ammonia, shows no consistent difference between the western yellow pine lands and the brush lands. It is likewise impossible to point to the hydrogen-ion concentration (pH) as a vitally important factor in limiting the occurrence of western yellow pine. The pH exponent indicates that in all cases under study in southern Utah, northern Arizona, and Colorado, western yellow pine was found growing on either neutral or alkaline soil. For Deadman's Gulch soil on the Pike National Forest in Colorado a pH value as high as 9.1 was recorded.

Natural reproduction was less abundant and less vigorous, however, on the more alkaline soils. This condition was noted particularly on the arenaceous limestone area south of Flagstaff, Ariz., in the Coconino National Forest, Lower Joe's Valley in the Manti National Forest, Sweetwater Canyon in the Sevier National Forest, Oak Creek in the San Isabel National Forest, and Deadman's Gulch in the Pike National Forest.

## SENSITIVENESS OF WESTERN YELLOW PINE TO SOIL CONDITIONS

In view of the close relationship already shown to exist between the range of western yellow pine and rainfall distribution, it is not surprising to find this species readily affected by the factors which influence soil moisture. The way in which it extends down stream courses into climatic zones elsewhere too dry is a universal expression of the need of ample soil moisture. Watson (*51*) has noted this particularly in Arizona and New Mexico and finds that soil moisture is the primary factor involved. At the same time western yellow pine reproduces and develops best on light soils, even where water supplies are ample, and there is accordingly considerable evidence that soil factors other than those strictly affecting moisture content exercise a considerable influence upon the species. For example, in an experiment (*2*) carried out at the Great Basin Experiment Station,[3] survival of seedlings was much the best on light porous soils, even though all were watered so thoroughly and frequently that the wilting point was never approached and the water-holding properties of the soil presumably had no influence on the development of the seedling.

Pearson (*37*) also notes that pine reproduction in Arizona and New Mexico is uniformly better on the coarser sandy and gravelly or stony soils than on finer soils. Since the finer soil materials are deposited

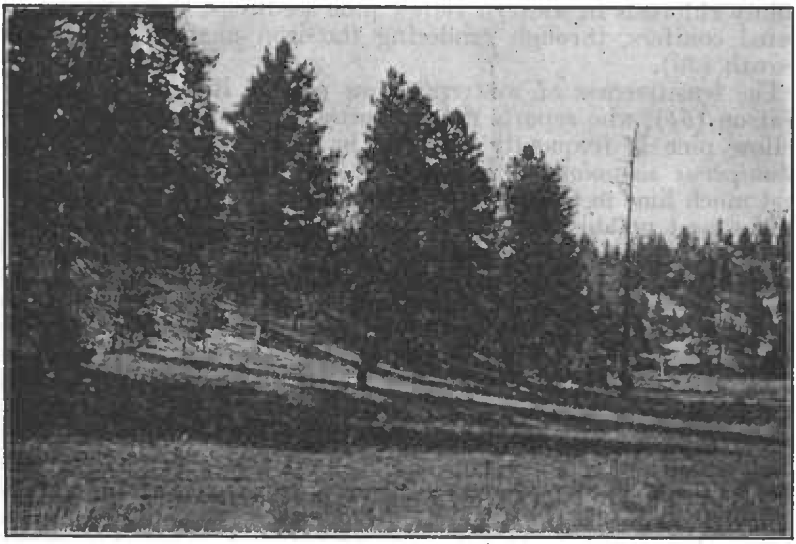

FIGURE 10.—Western yellow pine of good development on open, porous, gravelly slope soils, giving way to grass and sagebrush on heavier, finer-textured, more compact soils of the flats. (Sevier Plateau, Sevier National Forest, Utah)

in the valleys and flats, reproduction is usually poorer in such situations than on slopes. The writers have repeatedly noted that small ravines and depressions that usually have a silty soil support little if any western yellow pine, though the sandy or gravelly slopes a few yards away bear well-stocked stands. (Fig. 10.) On rocky, stony soils reproduction is often excellent; the deepest and most fertile soils, which ultimately produce the best stands, may be unfavorable to the establishment of seedlings. A detailed study carried out on a sample plot showed a progressive increase in the number of seedlings to the acre with increased proportions of gravel and stone in the clay soil. This is in a region where conditions are favorable to the germi-

[3] Now a field station of the Intermountain Forest and Range Experiment Station.

nation and growth of western yellow pine seedlings. Many other investigators have noted the same tendencies.

In Washington and adjacent Idaho, Larsen (*31*), Piper (*40*), and Weaver (*53*) found that western yellow pine exhibited a marked preference for soils of granitic origin, and that wherever such soil is found, even if completely isolated, western yellow pine is almost sure to occur, whereas this species encroaches on the clayey soils with difficulty.

Plantations in the oak-brush region show much higher survival in light soils than in heavy ones with prevailingly better moisture conditions, as will be shown later.

Detailed studies to determine the effect of lime, especially in large quantities, upon the growth and development of western yellow pine, have not been carried out. It has been shown, however, that an extremely high lime content in the soil, as in certain heavy calcareous loam and clay soils[4] in the brush lands of central Utah, may induce chlorosis in western yellow pine seedlings, as well as in associated conifers, through rendering the iron unavailable for plant growth (*30*).

The sensitiveness of western yellow pine to lime is also noted by Watson (*51*), who reports that in north-central New Mexico western yellow pine is frequently replaced by Rocky Mountain red cedar (*Juniperus scopulorum*) along lime-charged streams. It is clear that much lime in the soil is unfavorable to western yellow pine.

The most notable instance in the entire region where qualities of soil extend or limit the distribution of western yellow pine is in the long strip of isolated occurrences extending northward along the eastern edge of the Fishlake and Wasatch Plateaus. Here, upon sandstone cliffs, this species extends far beyond the region where it is generally found and loosely connects with the bodies in the Uinta Mountains. Outside of the stream bottoms it is hardly ever found in the brush-lands belt except on sandy soils. In the pineless area in the upper part of the Snake River plain the western yellow pine would apparently have sufficient rainfall, and its absence may reasonably be attributed to unfavorable soil. The soil of these rolling plains below the mountains is compact and heavy, and the mountain conifer types, such as Douglas fir and lodgepole pine, stop abruptly where the heavier soil of the plain is reached. Evaporation is also somewhat higher in this region than it is farther west, where yellow pine is found under virtually the same rainfall conditions.

It is thus evident that a strong influence is exerted by the soil upon the local distribution of western yellow pine. A light, sandy, or rocky soil has decidedly a favorable effect, whereas a heavy close-textured one is distinctly unfavorable and may even exclude western yellow pine where the rainfall is only slightly unfavorable. Although the relative importance of the presence of lime in the soil in limiting distribution is not definitely known, lime is clearly most effective under a light rainfall that favors its accumulation in the upper soil layers.

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[4] Such accumulations are usually found in swales where the rainfall has been insufficient to leach the soluble salts from the soil. Soils derived from limestone in the Southwest do not show nearly so pronounced a lime reaction, presumably because the lime is washed from the upper soil layers by the heavier rainfall.

## A SPECIFIC TEST OF THE INFLUENCE OF MOISTURE AND SOIL

The relation of western yellow pine to rainfall distribution and soil characteristics has been further tested by the study of a specific case, the results of which confirm the correctness of the general investigation by supporting the conclusion that soil, especially in its moisture relations, frequently governs the local distribution of the species. In this test a study was made of climatic factors at two stations some 25 miles apart on the Wasatch Plateau, in Utah, one in the oak-brush belt of Ephraim Canyon on the west slope and the other in an outlying body of western yellow pine on the east slope of the plateau.

In the western yellow pine type a cooperative Weather Bureau station was operated through the summer seasons of 1917, 1918, and 1919; the oak-brush station was the transition-zone station of

FIGURE 11.—The pines climatological station on the Manti National Forest, Utah. Here the ground cover is composed mainly of short, scrubby sagebrush (Artemisia). Much of the thin, sandy soil in the vicinity of this station, however, supports a scattered ground cover consisting chiefly of manzanita (Arctostaphylos) and bitterbrush (Purshia)

the (then) Great Basin Experiment Station. This climatological station was equipped with a rain gage and a standard instrument shelter, containing a thermograph and maximum and minimum thermometers. (Fig. 11.)

The oak-brush station is situated in the middle of the typical oak-brush zone at an elevation of 7,100 feet. The locality is characterized by an extensive slope having a generally western exposure broken into an undulating surface by low east and west ridges. The station is located on a gentle southern exposure of one of these ridges. The pines station was situated at an elevation of 8,200 feet upon an extensive, almost level sandstone bench, the greater part of which is covered by a pure stand of western yellow pine of somewhat inferior development.

The soil in the oak-brush zone of Ephriam Canyon is calcareous and heavy, much of it being silt loam, clay loam, or clay. Its wilting coefficient is about 15 per cent. At the pines station the soil is very light and very sandy, as reflected by a wilting coefficient of 3.3 per cent. This difference is obviously of considerable importance in determining the suitability of the two sites for western yellow pine.

The pines station, as might logically be expected, has much the lower mean temperature throughout the growing season. This, however, is owing rather to abnormally low mean minima than to low maximum temperatures. (Table 6.) These abnormal minima were peculiar to the pines station; elsewhere in this locality temperatures are very similar to the higher western yellow pine type in Arizona (*36*). The explanation probably lies in the poor air drainage on the western yellow pine flat, which is tilted down slightly to the west toward the high mountains. The belt above the oaks stations on the west slope of the range, which has the same temperature characteristics as the pines station, is covered with the Douglas fir type—aspen, white fir (*Abies concolor*), and Douglas fir.

TABLE 6.—*Temperatures in degrees Fahrenheit at the pines and oaks stations in the Manti National Forest, central Utah*

MEAN MAXIMUM TEMPERATURES

| Month | 1916 | | 1917 | | 1918 | | 1919 | |
|---|---|---|---|---|---|---|---|---|
| | Pines | Oaks | Pines | Oaks | Pines | Oaks | Pines | Oaks |
| May | | | | | | | 64.7 | 67.8 |
| June | | | | | | | 71.7 | 81.0 |
| July | | | 78.5 | 83.8 | [1] 73.4 | 79.0 | 76.6 | 83.9 |
| August | | | 73.4 | 79.9 | [2] 74.0 | 79.9 | 76.0 | 80.4 |
| September | | | 63.4 | 70.9 | 61.5 | 71.8 | 65.0 | 72.0 |
| October | 52.4 | 52.9 | | | [3] 51.0 | | | |

MEAN MINIMUM TEMPERATURES

| Month | 1916 Pines | 1916 Oaks | 1917 Pines | 1917 Oaks | 1918 Pines | 1918 Oaks | 1919 Pines | 1919 Oaks |
|---|---|---|---|---|---|---|---|---|
| May | | | | | | | 33.4 | 36.0 |
| June | | | | | | | 33.6 | 48.0 |
| July | | | 45.9 | 54.3 | [1] 45.5 | 52.1 | 43.1 | 55.5 |
| August | | | 40.8 | 49.9 | [2] 40.1 | 50.1 | 43.3 | 52.1 |
| September | | | 33.6 | 43.2 | 30.3 | 44.0 | 36.9 | 48.0 |
| October | 28.6 | 29.6 | | | [3] 28.1 | | | |

[1] Eight days' records missing. [2] Six days' records missing. [3] Four days' records missing.

The summer temperatures at the oaks station are similar to those in the lower western yellow pine type and the upper piñon-juniper type in Arizona. This is further evidence that it is not temperature that keeps western yellow pine out of the oak-brush type, although the higher temperatures naturally tend to make moisture deficiencies more difficult to withstand.

As already shown the total precipitation and its distribution throughout the year are of great importance in determining the range of western yellow pine. Because the precipitation records at the pines station cover so short a period, data for the older Weather Bureau stations at Emery and Manti,[5] the two valley stations nearest

[5] Emery is about 6 miles distant from the pines station and 2,000 feet lower. Manti is about 8 miles distant from the Ephraim Canyon oak-brush station and is 1,300 feet lower.

to the pines and oak-brush stations, are used to show the seasonal distribution of precipitation. (Fig. 12.) The distribution of rainfall at Emery resembles that of the south plateau type, especially in summer. It has a single culmination in August, which rises from a flat minimum lasting from November until the following June. The precipitation at Manti is typical of that of the central plateau type, having the lowest spring record in May, a secondary rise in September, and a well-defined minimum in June. This indicates that, while normally the pines station suffers as extreme drought as the oak brush in June, in July it is fully as wet, and in August is much better watered. Of all the growing season, May seems to be least favorable at the pines station. However, because of the elevation (8,200 feet) moisture from melting snow is abundant at the pines station in May and early June. Given equal annual precipitation,

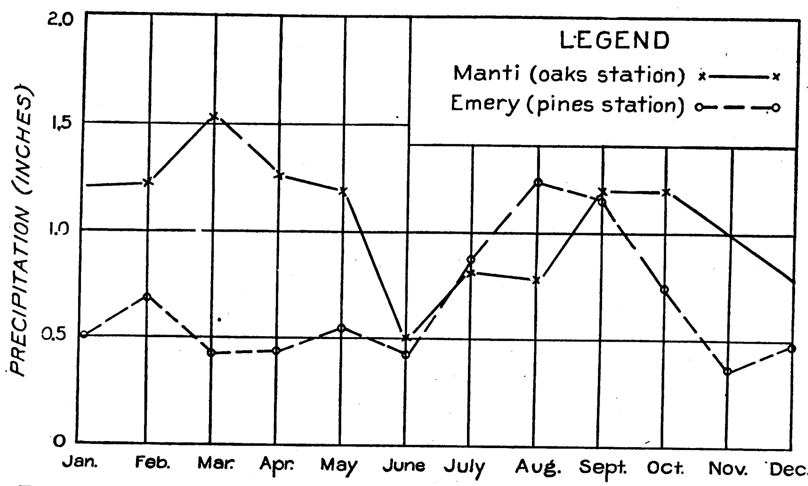



FIGURE 12.—March of mean monthly precipitation at Manti near the oaks station and at Emery near the pines station on the Wasatch Plateau. The means for Manti cover the period from 1892 to 1920, while those for Emery are for the period from 1901 to 1920

the type of rainfall at Emery is obviously more efficient than that at Manti.

The true explanation of the presence of western yellow pine in one place and its absence in the other apparently lies in the combined influences of the following factors that favor the pine over the oak at the pines station and have opposite effects at the oaks station.

At the pines station the low minimum temperatures in the spring, coupled with moderate maxima, tend to delay snow melting and yet allow growth to proceed in frost-resistant species like western yellow pine. These low spring temperatures and the late frosts apparently prevent normal fruiting of the oak brush.

The July precipitation probably results in no great deficit in the western yellow pine type, at least not to the extent that it does in the oak brush. In August the pines area receives considerably more rain than the oak-brush station.

The sandy soil at the pines station is more suitable to the germination and early growth of western yellow pine than the heavy calcareous soil of the oak-brush belt; also its porosity and flat surface permit a very complete absorption of rainfall.

The sandy soil loses water by evaporation more slowly than the heavier clay loam.

The underlying iron-cemented sandstone layer at the pines station is nearly horizontal and full of pits and hollows, hindering complete subterranean drainage, whereas the subsoil in the oak-brush type is permeable and extends very far down.

At the pines station, western yellow pine has little competition from other conifers or from large shrubs for the scanty water supplies of the upper soil. Sagebrush or other smaller vegetation will not grow luxuriantly on the relatively infertile, thin, sandy soil.

## RESULTS OF PLANTINGS

The more important conclusions of the study of climatic and soil conditions at the pines and oaks stations on the Manti National Forest and on other western yellow pine lands and brush lands were tested further by a special investigation of the possibility of forestation within the brush zone. Experience in these and in other forestation studies has shown that planted stands often develop normally in regions where natural regeneration is impossible. The fact that the brush lands are not natural western yellow pine sites, therefore, would not necessarily preclude successful planting. Indeed, the importance of the factor found to be chiefly responsible for the absence of western yellow pine in the brush lands—insufficient soil moisture in the upper soil layers during a short critical period immediately following germination—may in some cases be very greatly reduced in planting.

Although early field plantations had yielded surprisingly poor results—a heavy loss almost invariably occurring during the first few years (*29*)—experimental plantings were made on a number of different sites within the brush belt to confirm these results and to determine what sites were most suitable for the introduction of western yellow pine.

### EXPERIMENTAL PLANTATIONS

Plantations were established in the oak-brush belt in Ephraim Canyon on the Manti National Forest in central Utah, in the oak-brush belt on the Beaver Creek watershed at the west end of the Uinta range, and on various brush areas in Big Cottonwood Canyon in the Wasatch Mountains in northern Utah, as well as on the Mink Creek watershed about 10 miles southwest of Pocatello on the Cache National Forest in southern Idaho. The Ephraim Canyon watershed was studied most intensively, but sufficient work was done on the other areas to serve as a check on the major study and in some ways to supplement it.

#### EPHRAIM CANYON WATERSHED, MANTI NATIONAL FOREST, CENTRAL UTAH

##### Procedure

A compact area at an elevation of approximately 7,400 feet in the middle of the oak-brush type was selected on the Ephraim Canyon watershed. The mean annual temperature here is approximately

42° F., and the climate during the growing season resembles that of the lower western yellow pine or upper piñon-juniper type of northern Arizona. The mean annual precipitation is 17.81 inches (1914–1919). The greater part of this falls during the winter in the form of snow. The site usually becomes free of snow about April 15, after which occasional snows and rains occur until the middle of May. After this comes a period of drought usually lasting until the latter part of July or early August. During this period cloudless weather prevails, although occasional light showers may occur, especially in late May and early July.

Five main sites were selected in 1917 for this experiment, and another was added the following year. These sites are located in a small basin having a generally western exposure. (Pl. 1, B.) The sandstone and residual clay of the ridge bounding the basin on the north give rise to a very shallow, infertile, light-colored soil having a relatively small admixture of humus. To the south the bounding ridge is of nearly pure limestone and has a darker soil containing more clay. The sites selected were as follows:

(1) On the top of the ridge to the north of the basin, in a low cover of manzanita (*Arctostaphylos pungens*) not over 18 inches in height; between the clumps of brush, extensive open spaces practically without vegetation.

(2) Immediately south of the preceding site on the slope of the ridge, where squaw-apple, locally known as wild apple (*Peraphyllum ramosissimum*) and common mountain-mahogany (*Cercocarpus montanus*) predominate; considerable areas of bare ground between the clumps. On both this and the preceding site scattered piñon pine and Utah juniper are found.

(3) A sagebrush (*Artemisia tridentata*) flat in the bottom of the basin, having a deep black clay loam soil which becomes very hard and dry in summer. (Pl. 2, A.) The cover is moderately dense sagebrush, 2 to 2½ feet tall.

(4) A site similar to the third but from which the sagebrush and all other vegetation was removed with a grubbing hoe.

(5) A short slope with western aspect covered with thrifty oak brush (*Quercus utahensis*) from 6 to 10 feet tall; soil of limestone origin and well supplied with humus, particularly in the immediate vicinity of the oak clumps.

(6) An oak-brush site on the steep north-facing slope of the ridge bounding the basin on the south. Sites similar to this commonly bear scattered Douglas fir, white fir, and Rocky Mountain red cedar, although none occur on the particular area planted.

On each of the first five sites one hundred 2–1 western yellow pine transplants[6] were planted in the spring of 1917; the same number was planted on all six sites in the spring of 1918. A 2-year record of evaporation on these sites was obtained by means of Shive's (*47*) improved form of the Livingston standardized rain-correcting porous-cup atmometer (*33*). Soil samples were taken often enough to show the march of soil moisture during the growing season.

The results of these plantings, expressed in survival, vigor, and growth rate, are given in Table 7. They indicate considerable differ-

[6] Seedlings grown two years in the seed bed and one year in the transplant bed.

ence in the suitability of these brush-land sites for the planting of western yellow pine. Taking into account all the combined evidence on survival, vigor, and growth rate, the best results were obtained on the cleared sage site. Here the survival was highest, growth most rapid, and the increase in vigor most marked between the third year and the time of the last examination. Where the sage was not cleared there was a heavy mortality, but the transplants which survived, as evidenced by the increase in vigor and growth rate, became well rooted and capable of competing successfully with the sagebrush.

TABLE 7.—*Survival, vigor, and rate of height growth in plantations of western yellow pine on oak-zone sites in Ephraim Canyon, Manti National Forest, Utah*[1]

| Site | Survival | | | | | Proportion of vigorous trees to number of survivors | | Average annual height growth | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | First year | Second year | Third year | Fourth year | Last year[2] | Third year | Last year[2] | First year | Second year | Third year | Fourth year | Last year[2] |
| | P. ct. | P. ct. | P. ct. | P. ct. | P. ct. | P. ct. | P. ct. | Inches | Inches | Inches | Inches | Inches |
| (1) Manzanita | 62 | 54 | 50 | 47 | 32 | 66 | 46 | 0.40 | 0.50 | 0.61 | 0.39 | 0.50 |
| (2) Squaw-apple | 72 | 50 | 44 | 41 | 19 | 46 | 54 | .22 | .26 | .45 | .50 | .80 |
| (3) Sagebrush | 57 | 46 | 42 | 22 | 19 | 65 | 98 | .18 | .59 | .46 | .89 | 2.43 |
| (4) Cleared sagebrush | 68 | 58 | 51 | 46 | 39 | 34 | 68 | .21 | .91 | 1.47 | 2.59 | 10.19 |
| (5) Oak (west aspect) | 77 | 52 | 39 | 23 | 15 | 85 | 27 | .22 | .65 | .67 | .85 | .62 |
| (6) Oak (north aspect) | 92 | 79 | 64 | ------ | 28 | 45 | 46 | .62 | .44 | .98 | ------- | 1.09 |

[1] One hundred transplants were planted on each of the sites in May, 1918, on each of the sites except he oak (north aspect) in May, 1917, and on the manzanita site alone in April, 1916.
[2] The last examination of all the sites was in the autumn of 1924, seven growing seasons after the last planting.

Reduction in vigor, accompanied by very slow growth, is to be noted in the manzanita and west-aspect oak-brush plantations. The latter, together with the wild apple and uncleared sage sites, shows a very low survival.

## FACTORS INFLUENCING RESULTS

The usually heavier mortality during the first year, shown in Table 7, suggested that certain factors were especially influential during that period and that perhaps there was a difference between the causes of initial mortality and those leading to later losses. A study was accordingly made of several of these—soil moisture, evaporation, soil texture, light, and damage by snowshoe rabbits—to determine their influence upon the survival and development of the planted pine. In general, soil moisture was found to be the most important at all times and particularly during the first year. Evaporation and soil texture, also, were more effective the first year than later; rabbit injury and light became more important later on.

### SOIL MOISTURE

The moisture available for plant growth, rather than the total moisture present in the soil, has been taken as the significant index in this work. The wilting coefficient of all the soils was determined in the biophysical laboratory of the Bureau of Plant Industry, United States Department of Agriculture, by the Briggs and Shantz centrifugal method (*8*). The available moisture at a depth of 6 to 12 inches is considered of the greatest importance because the transplants have no feeding roots in the upper 6 inches of soil (*26*). The seasonal march of available soil moisture at a depth of 6 to 12 inches

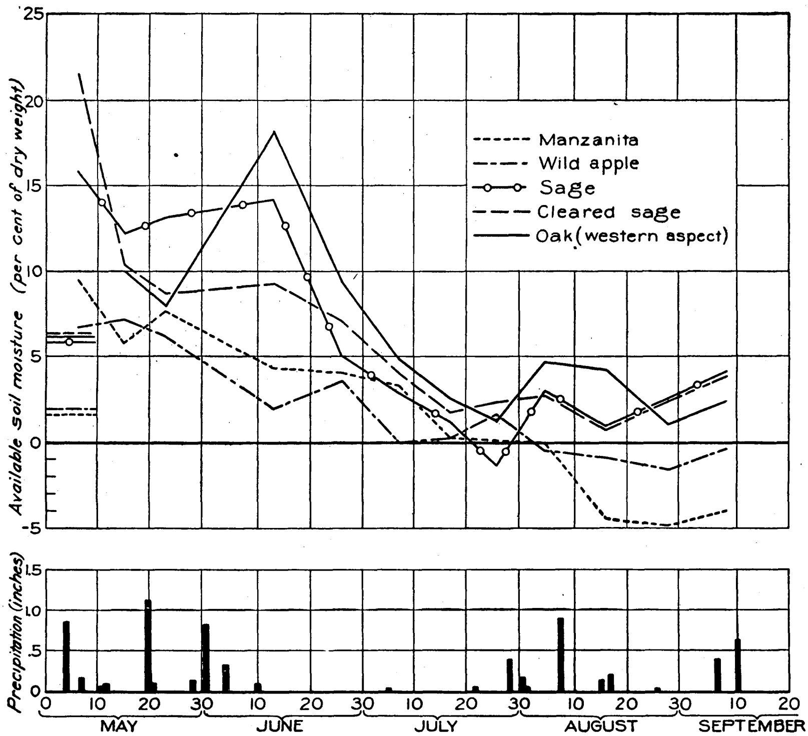



FIGURE 13.—March of available soil moisture at depth of 6 to 12 inches and daily precipitation, oak-brush zone, Ephraim Canyon watershed, Manti National Forest, Utah, season of 1917. (Seasonal average shown by horizontal lines at left of graph)

on the several sites, together with the daily precipitation for the growing seasons of 1917 and 1918, is shown graphically in Figures 13 and 14, respectively, and the curved averages for those sites in the oak-brush zone which have two or more season's record are shown in Figure 15. The mean total soil moisture and wilting coefficients at the 6 to 12 inch depth for the growing seasons of 1917 and 1918, and a summary of the evaporation data for the seasons of 1917, 1918, and 1919, are given in Table 8.

TABLE 8.—*Summary of soil-moisture and evaporation data on experimental planting areas, Ephraim Canyon watershed, Manti National Forest, Utah, growing seasons of 1917, 1918, and 1919*

| Site | Mean seasonal total soil moisture at depth of 6 to 12 inches | | | Wilting coefficient of soil[1] | Mean daily evaporation | | | | $\frac{E}{SM}$[2] |
|---|---|---|---|---|---|---|---|---|---|
| | 1917 | 1918 | Average | | 1917 | 1918 | 1919 | Average | |
| | *Per cent* | *Per cent* | *Per cent* | | *C. c.* | *C. c.* | *C. c.* | *C. c.* | |
| (1) Manzanita | 13.9 | 11.7 | 12.8 | 12.1 | 33.4 | 37.86 | 43.2 | 38.15 | 2.98 |
| (2) Squaw-apple | 13.5 | 12.0 | 12.8 | 11.5 | 36.8 | 34.57 | 39.6 | 36.99 | 2.89 |
| (3) Sagebrush | 19.7 | 19.3 | 19.5 | 13.7 | 27.1 | 25.87 | -------- | 26.48 | 1.36 |
| (4) Cleared sagebrush | 20.4 | 22.7 | 21.6 | 12.1 | 31.3 | 33.64 | -------- | 32.47 | 1.50 |
| (5) Oak (western aspect) | 21.8 | 22.1 | 22.0 | 15.7 | 22.8 | 20.86 | 23.5 | 22.39 | 1.02 |
| (6) Oak (northern aspect) | -------- | 23.8 | 23.8 | 15.7 | -------- | 18.49 | 18.9 | 18.70 | .79 |

[1] Determined in the biophysical laboratory, Bureau of Plant Industry, U. S. Department of Agriculture by the Briggs and Shantz centrifugal method.
[2] Mean daily evaporation divided by the mean seasonal total moisture content of the soil at a depth of 6 to 12 inches.

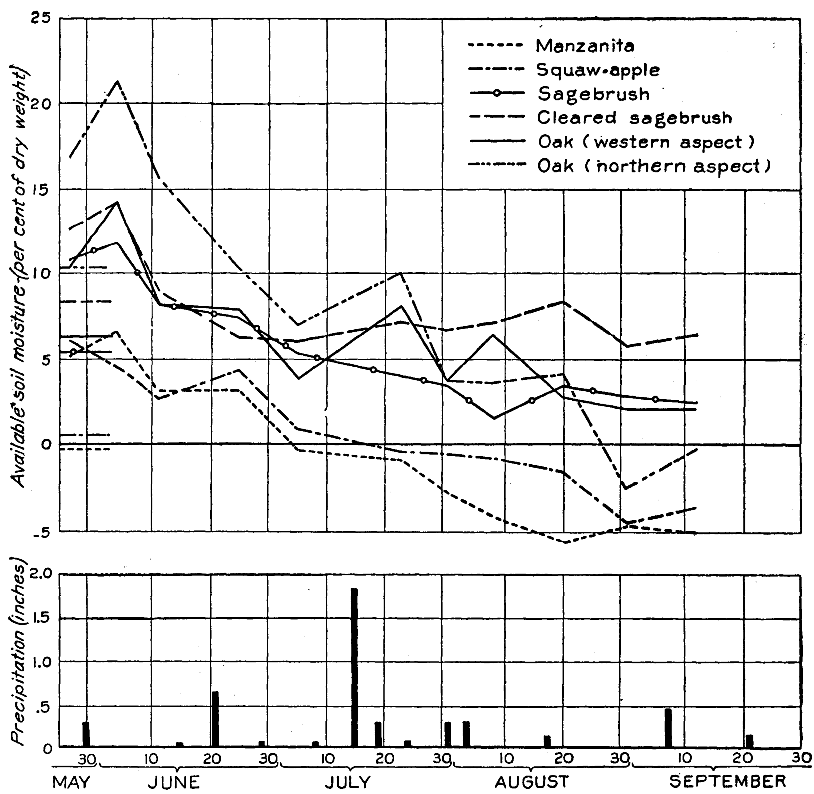
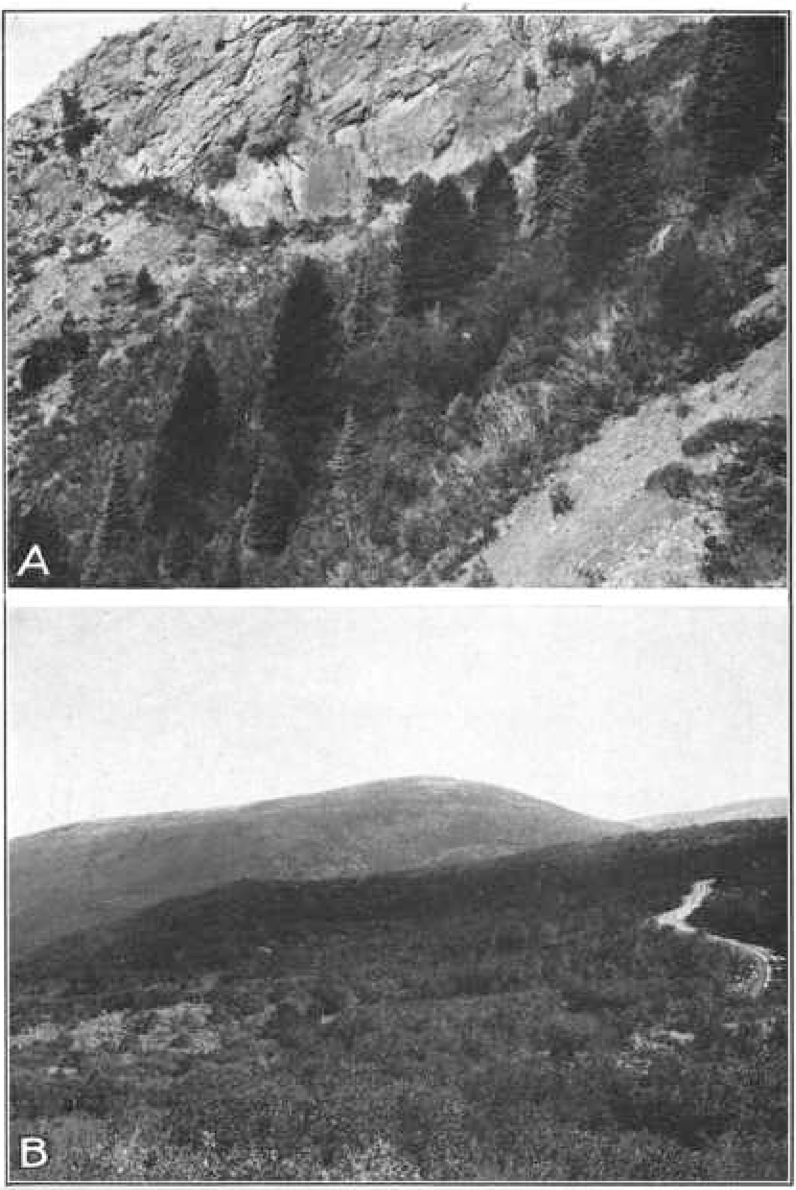


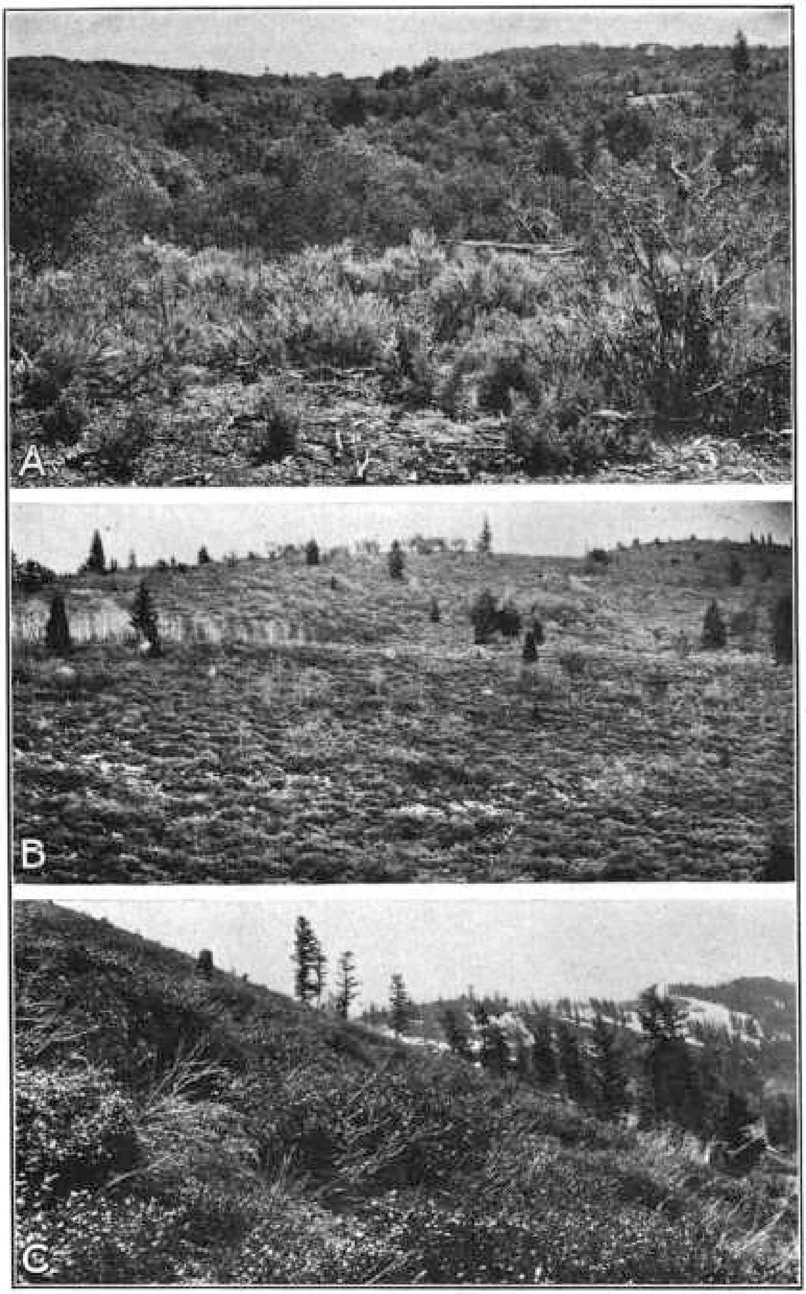

FIGURE 14.—March of available soil moisture at depth of 6 to 12 inches and daily precipitation, oak-brush zone, Ephraim Canyon watershed, Manti National Forest, Utah, season of 1918. (Seasonal average shown by horizontal lines at left of graph)

Figures 13 and 14 clearly show the meagerness of the rainfall and the resultant effect upon soil moisture. It is very apparent that the west-aspect oak site has generally the most available soil moisture,



F150939 F39963A

A, An outlying occurrence of the Rocky Mountain form of western yellow pine associated with white fir and limber pine on a steep southern aspect of coarse talus material in Whipple Gulch, Big Cottonwood Canyon, Wasatch National Forest, Utah. No yellow pine occurs on adjacent finer-textured soils; B, general view of oak-brush planting area in Ephraim Canyon, Manti National Forest, looking south across the sagebrush flat from the manzanita-covered ridge, with the oak-brush sites immediately to the left




F39962A F153347 F153345

A, A sagebrush flat in the oak-brush zone planted to western yellow pine with poor results, Ephraim Canyon, Manti National Forest, Utah; B, planting area on the southern aspect in the permanent brush type on the Big Cottonwood Canyon watershed suitable for western yellow pine, Wasatch National Forest, Utah; C, planting area on the western aspect of Big Cottonwood Canyon watershed, covered with temporary brush type characterized by snowbrush following logging and fire in the Douglas fir type, Wasatch National Forest, Utah except late in the growing season, when the heavy leaf canopy and the thick layer of absorptive duff prevent the addition of much water to the 6 to 12 inch soil layer. At this season also the activity of the oak roots is probably at its maximum. The cleared sagebrush area receives considerable water at this time, which in a measure compensates for the more rapid losses by evaporation from the unprotected soil earlier in the season. These losses, however, are much less than those from the sagebrush itself, where, although the soil is generally shaded, the water is drawn rapidly from the upper soil layers by the widespreading roots of the sagebrush. Soil moisture

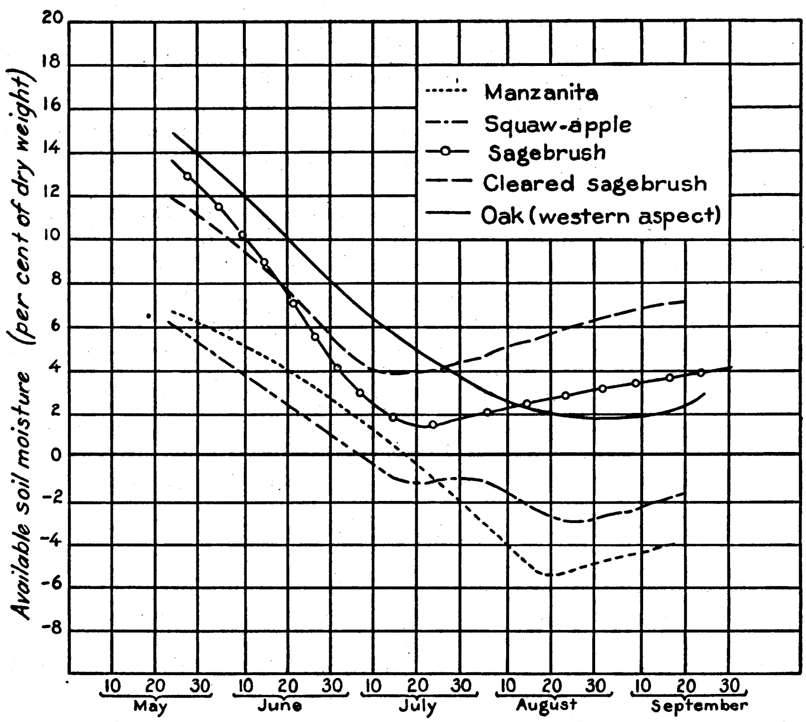



FIGURE 15.—Mean seasonal march of available soil moisture at depth of 6 to 12 inches for sites in the oak-brush zone, Ephraim Canyon watershed, Manti National Forest, Utah, having two or more seasons' record during the period of 1917 to 1919, inclusive

is thereby so depleted that, although the summer rains are absorbed as readily as on the cleared area, the resulting available moisture is considerably less.

Both the manzanita and the squaw-apple areas show a low soil-moisture content earlier in the season and a rapid loss throughout the dry period, the available moisture in the 6 to 12 inch layer being exhausted by early July. Both these soils are loose and absorbent and contain very few feeding rootlets in the 6 to 12 inch layer. The low moisture must be ascribed to rapid percolation and high evaporation in these hot, unprotected sites (*26*). A given amount of rain would penetrate more deeply in the light than in the heavier soil, and the portion which reaches the lower strata is less subject to evaporation. As long as the showers are light, there probably is not much difference; but a rainfall sufficient to penetrate 6 inches in the heavier soil would probably reach below a foot in the light soil, and a considerable proportion of this should still be available after it has all evaporated from the heavier soil. The greater permeability of the manzanita and squaw-apple soils would ordinarily suggest lower wilting coefficients [7] and more sustained survival than the records show.

A study of soil moisture in relation to survival at the end of the first year indicated fairly consistently that heavy losses the first year are occasioned by deficiencies in soil moisture, especially early in the season. Western yellow pine develops a root system that penetrates downward rapidly; and if it can keep pace with the falling moisture level the plant's survival is assured. Soil-moisture conditions at 6 to 12 inches are therefore of most importance during the period immediately after planting. From this time up to the last examination no pronounced correlation was apparent.

The excellent initial survival of the plantation on the west-aspect oak site (Table 7), and the still better survival on the one on the north aspect where, according to a single year's comparison, soil moisture is even more plentiful, is obviously correlated with the high moisture content of the soil. The relatively high survival on the squaw-apple site apparently is an exception. It should be noted, however, that there was considerable divergence in the first-year results as between the 1917 and 1918 plantations on this site. The heavy initial losses on the cleared sage and sagebrush areas the first year are difficult to justify on the basis of soil moisture alone, but losses on the manzanita site are obviously due to soil-moisture deficiency.

## EVAPORATION

Early in the study evaporation was believed to have considerable influence upon the behavior of these plantations. In Figures 16 and 17 the march of evaporation for the sites under study is shown graphically for the seasons of 1917 and 1918. The mean daily evaporation for the same seasons is shown in Table 8, from which it is evident that evaporation alone fails to clarify the problem. For example, there is high survival on the manzanita site, where evaporation is very high, and the losses in the sagebrush are much heavier than in the cleared sage area, which is open to the full intensity of the sunlight and the full sweep of the wind. Caldwell (*10*), Shive and Livingston (*48*), Livingston (*32*), and others, have shown that permanent wilting of succulent plants occurs with varying amounts of moisture in the soil, depending on the evaporation. In many of the conifers, however, permanent wilting is such a protracted process that extremely high evaporation for a few hours at a time does not appreciably affect the results. When the moisture in the soil ap-

[7] The difficulty of obtaining representative samples for analysis accounts, in part, for this apparent anomaly. Then, too, in the centrifugal method of determining moisture equivalent (from which the wilting coefficient is computed) all stones over 2 mm. in diameter are screened out before the soil is run through the centrifuge. Therefore, wilting coefficient alone, for a soil having considerable gravel, is not a particularly good index of permeability. The simple tests described on pp. 36 and 37 show the soils on the manzanita and squaw-apple sites to be very permeable in comparison with the soil of the sagebrush site.

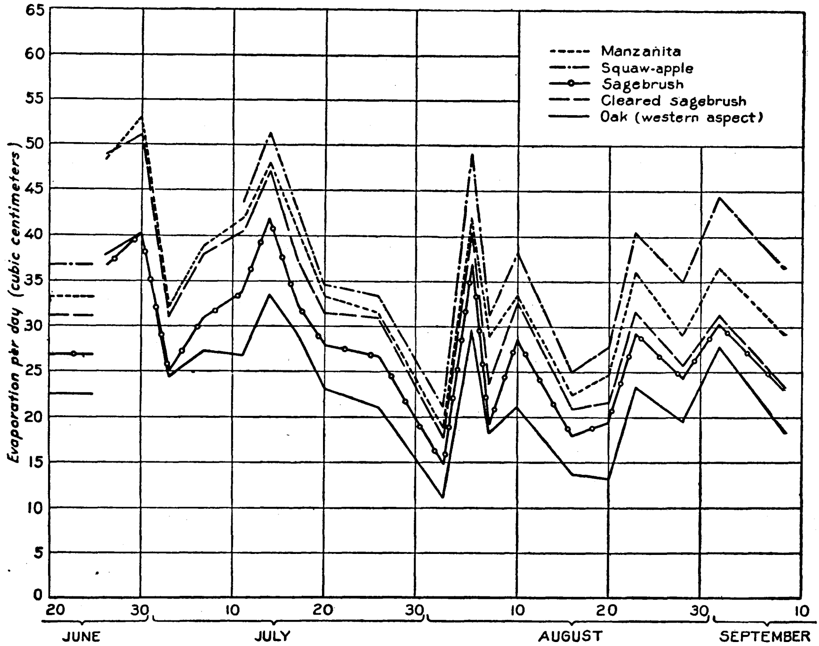



FIGURE 16.—March of evaporation, oak-brush zone, Ephraim Canyon wateıshed, Manti National Forest, Utah, season of 1917. (Seasonal averages shown by horizontal lines at left of graph)

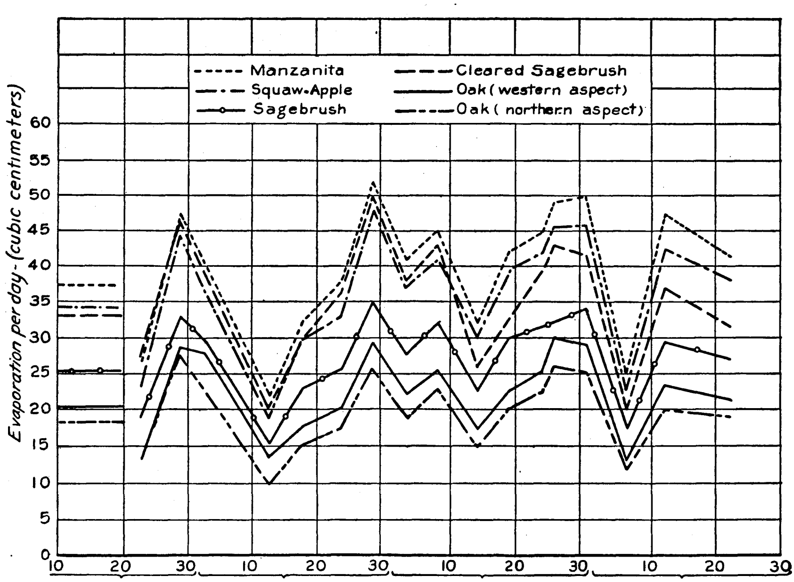



FIGURE 17.—March of evaporation, oak-brush zone, Ephraim Canyon watershed, Manti National Forest, Utah, season of 1918. (Seasonal averages shown by horizontal lines at left of graph)

proaches the wilting coefficient, transpiration is reduced to almost nothing, and western yellow pine seedlings may stand for weeks before they finally succumb.

A satisfactory expression of the moisture relations of the site according to Fuller (*18*) and Shreve (*49*) may be obtained through the expression " evaporation divided by soil moisture," expressed as $\frac{E}{SM}$. (Table 8.) In the present study this coefficient shows little correlation with the success of the plantations, the factor E alone serving to confuse rather than clarify. The poor correlation between survival and evaporation is, in part at least, explained by the fact already mentioned, that if the western yellow pine roots are functioning properly this species can withstand prolonged and intense evaporation with only a small margin of soil moisture above the wilting coefficient. It is unreasonable, however, to conclude that high evaporation is not effective in reducing the survival of newly planted trees, for on otherwise similar sites the greatest loss would undoubtedly be found where evaporation was highest. In these particular cases variations in soil moisture serve in general to neutralize the effects of the variations in evaporation intensity. Where soil moisture fails to explain survival there seem to be other, rather ill-defined factors, apparently in the soil, which are of greater importance than evaporation and which further serve to obscure the effects of evaporation.

### SOIL TEXTURE

From the results of the study of soil conditions in the western yellow pine type and the brush lands one would naturally expect that soil texture would influence the survival and vigor of western yellow pine on these sites, aside from its effect upon the water relations, and that light porous soils would be much more favorable than heavy clay soils. However, it is difficult to conclude from Table 7 that survival and vigor during the first 5 to 10 years after planting are materially better on the light soils than on the heavier ones. No special study of the porosity and structure of these soils was made, although when digging the holes for planting the trees it was plainly evident that there were great differences, the sagebrush and oak-brush soils being dark, compact, and without visible gravel, whereas the manzanita and squaw-apple soils were much lighter in texture, the squaw-apple in particular being stony. As shown in Table 5, the sagebrush and oak-brush soils both have a water-holding capacity of between 62 and 63 per cent and the manzanita and squaw-apple soils of only 49.4 per cent.

These differences are also reflected in the results of a simple test which may be considered indicative of the permeability of the soil. In this test, cylindrical holes, 1.5 inches deep and 1.5 inches in diameter, were made in the soil. Water was run into these holes from a 50 cubic centimeter burette until the hole was full. Then water was added to keep the hole full until all of the 50 cubic centimeters was used. The time was noted from the start of filling the hole until 50 cubic centimeters had been run in and had been completely absorbed. The results were as follows: Oak-brush soil, 47 seconds; manzanita soil, 71 seconds; squaw-apple soil, 64 seconds; and sagebrush soil, 190 seconds. The point of particular interest in this test is the rate of absorption in the manzanita and squaw-apple soils as compared with that in the sagebrush soil. The extreme rapidity of absorption in the oak-brush soil was due mainly to the humus in the surface layer. On the other sites the topsoil is virtually homogeneous. The manzanita and squaw-apple soils are much lighter and more permeable than the sagebrush and oak-brush soils, and this probably explains, in part at least, the disparity between survival on these sites and the results of the soil moisture and evaporation studies on the same sites. As already pointed out, a permeable soil favors conservation of moisture by allowing deep penetration. In a deep-rooted species such as western yellow pine this should be an important asset. Doubtless aeration and lime content are also important.

Soil texture largely determines soil aeration. According to Cannon and Free (*12*) different species of plants may differ markedly in their response to variations in the composition of the soil atmosphere, either through a decrease of oxygen or an increase in carbon dioxide content, and hence to changes in soil aeration. Soil aeration is frequently a factor of no less importance than soil moisture and at greater depths even affects the moisture content.

In a porous soil, other things being equal, the lime content is less, because deep penetration of moisture prevents concentration of the lime in the major root zone. The high lime content of the compact, heavy, poorly aerated clays and clay loams found in swales and flats in the oak-brush zone is doubtless a contributing factor to the poor survival and growth on these sites. As has already been noted, western yellow pine planted in such places is subject to chlorosis, a trouble that has been clearly correlated with an excessive lime content in the soil (*30*).

Inadequate soil aeration and a high lime content therefore offer possible explanations of the effect that soil texture has upon the development of western yellow pine.

### SNOWSHOE RABBITS

The damage from snowshoe rabbits was considerable, but was confined to plantations located in tall brush, since the rabbits are too timid to venture far from the protection of the high bushes into the relatively open sagebrush and manzanita areas (*3*). Although the small trees whose tops are cut off repeatedly persist in sending out new shoots they have little chance to regain their lost vigor and to increase their height growth. Injury from rabbits has been responsible for a reduction in the vigor and growth of the plantations on the oak and squaw-apple sites, and poor growth and development on the brushy plots may be ascribed in part at least to the rabbits; but other studies have revealed the fact that even repeated damage of this kind on sites suitable to the planted trees causes little mortality. The continued mortality on these sites can not apparently be charged directly to the rabbits.

### LIGHT

Much of the lack of vigor and the continued mortality on the denser brushy sites is probably due to insufficient light, since western yellow pine is intolerant of shade and attains its best development in full light.

The difference in vigor between the trees on the oak-brush areas and those on the other plantations is very striking, and is even more marked than the figures in Table 7 indicate. On the sagebrush and cleared sagebrush areas in particular the trees are vigorous and stocky. On the other hand, in the oak brush the new growth is spindling, and the trees which show the most rapid height growth are unable to stand erect. The leaves are few, short, and light green, whereas the pines in the open have many long, stiff, deep-green leaves. The high initial survival, due to ample soil moisture and low evaporation in the oak brush, has been offset by too much shade, which will probably wipe out the plantations in a few years.

### RELATIVE SIGNIFICANCE OF FACTORS

The survival, growth, and vigor of the plantations on the different sites in Ephraim Canyon can not be fully explained by the study of site factors on these areas alone. The indications presented are, however, sufficient for the formulation of the following conclusions:

Initial survival is highest upon the sites having a high moisture content, especially in the early spring. This gives the planted trees a chance to become established and to develop roots in the deeper soil layers before extreme dryness occurs. Low evaporation also favors initial survival.

Survival after the first year is largely determined by factors influencing the development of the root system and by those affecting photosynthesis. Variations in soil moisture, as indicated by the content of the 6 to 12 inch layer, are much less significant after the first year, whereas soil texture becomes more important—light porous soils especially favoring the growth and development of western yellow pine.

The effect of shade becomes apparent after the first year, especially in the oak brush. A very dense cover prevents normal growth and so weakens the trees as to make them very sensitive to other unfavorable factors, such as unfavorable soil conditions and damage from rodents.

In the oak-brush areas high soil moisture and low evaporation make possible good initial survival, but in the second year losses from a deficiency of light begin. It is significant that trees in the center of the oak clumps die first of all, while those situated in openings between the bushes persist the longest and often succeed in becoming established. Trees in the dense brush can less often survive severe rabbit damage, since in their weakened condition they are unable to develop new vigorous shoots.

In hot, dry situations, such as the manzanita and squaw-apple sites, which are characterized by infertile porous soil, heavy initial losses are to be expected, to be followed by a lower mortality. Site conditions, however, are severe, and the infertile soil prevents rapid growth. The trees remain small; and in spite of a favorable soil texture moderate losses will probably continue.

In the sagebrush areas, also, heavy initial losses are to be expected, owing to the rapid drying out of the surface layers through root competition. The trees which survive, however, will make good growth because of the rich soil characteristic of these areas.

When the sagebrush is cleared off the planting site, soil moisture is increased through the removal of the root competition of the sagebrush, even though evaporation is somewhat accelerated. As a result lower initial losses are to be expected, and, lacking the keen competition of the sagebrush, the plants become vigorous almost at once and grow rapidly.

These conclusions, derived from the experimental plantations in the oak-brush zone in Ephraim Canyon, have been checked by the results obtained at other points in the region where less intensive studies were made.

### BIG COTTONWOOD CANYON, WASATCH NATIONAL FOREST

The results of plantations on the Big Cottonwood watershed of the Wasatch National Forest in northern Utah were in many respects almost as significant as those obtained in Ephraim Canyon. Here western yellow pine was planted experimentally on sagebrush-snowbrush-oak-aspen and snowbrush-oak areas in 1913, 1915, 1916, 1918, 1919, and 1920, with the results shown in Table 9. Most of the plantations comprised 100 trees each, although a few of the plots had 200 trees.

TABLE 9.—*Record of experimental plantations of 2–1 western yellow pine on the Wasatch National Forest, Utah*

BIG COTTONWOOD CANYON WATERSHED

| Site | Date planted | Survival at time of examination in— First year | Second year | Fourth year | Proportion of vigorous trees to number of survivors, last examination | Average height growth last year observed |
|---|---|---|---|---|---|---|
| | | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *Inches* |
| Sagebrush-snowbrush-oak-aspen | Oct. 25, 1913 | 96 | 88 | [1] 68 | 44 | 0.9 |
| | Oct. 15, 1915 | 67 | 51 | [2] 34 | 23 | .9 |
| | Apr. 28, 1918 | 73 | 44 | | 39 | .2 |
| | May 14, 1919 | 32 | 22 | | 15 | .4 |
| | Oct. 7, 1919 | 12 | | | 11 | |
| | Oct. 11, 1919 | 25 | | | 21 | |
| | May 24, 1920 | 92 | | | 89 | |
| | do | 88 | | | 83 | |
| Snowbrush-oak | Oct. 15, 1915 | 68 | 54 | [3] 40 | 32 | 1.0 |
| | May 14, 1916 | 70 | 45 | [4] 32 | 23 | .6 |
| | May 14, 1919 | 53 | 45 | | 28 | .2 |
| | May 15, 1919 | 13 | 10 | | 7 | .2 |
| | do | 23 | 20 | | 9 | |
| | Oct. 3, 1919 | 35 | | | 19 | |
| | Oct. 13, 1919 | 35 | | | 18 | |
| | May 26, 1920 | 85 | | | 71 | |
| | do | 91 | | | 65 | |

BEAVER CREEK WATERSHED

| Site | Date planted | First year | Second year | Fourth year | Proportion vigorous | Average height growth |
|---|---|---|---|---|---|---|
| Oak (west aspect) | May 29, 1917 | 81 | 74 | 55 | 28 | 1.4 |
| Cleared sagebrush | do | 92 | 86 | 46 | 27 | 1.4 |
| Sagebrush | do | 79 | 77 | 40 | 22 | .5 |

[1] 66 per cent the fifth year.
[2] 30 per cent the fifth year.
[3] 34 per cent the fifth year.
[4] 27 per cent the fifth year.

In Big Cottonwood Canyon the average rainfall for 11 years in the vicinity of the plantations for the period from May 1 to December 31 was 11.47 inches; June and July with less than 1 inch each, have the lowest monthly averages; August has 1.37 inches. Killing frosts frequently occur as late as June 15 and as early as September 1, and light frosts may occur throughout the entire summer. The soils are of limestone, granodiorite, and quartz diorite origin and range in texture from a gravelly or sandy loam to a loam. They are not excessively calcareous. The greater suitability of these sites for western yellow pine is further indicated by the presence of more mesophytic shrubs than are common in the oak-brush type in Ephraim Canyon.

The oak brush on this watershed is scattered and much more scrubby than in Ephraim Canyon and is associated with big sagebrush (*Artemisia tridentata*), snowbrush (*Ceanothus velutinus*), scattered aspen (*Populus tremuloides*), common serviceberry (*Amelanchier alnifolia*), black chokecherry (*Prunus melanocarpa*), blueberry elder (*Sambucus caerulea*), and other shrubs. (Pl. 2, B.) On this sagebrush-snowbrush-oak-aspen site the scattered aspen and the elder and chokecherry on the lower part of the site indicate a fairly good supply of soil moisture, probably derived from subterranean seepage within 3 feet of the surface. This, together with the light texture of the soil, should be favorable for western yellow pine. A few scattered Douglas fir and white fir are also found on the lower portion of the slope, although the greater part of the area appears to be potentially brush land.

On the snowbrush-oak site, which has a western aspect, chokecherry, serviceberry, mountain snowberry (*Symphoricarpos oreophilus*), and mallow ninebark (*Opulaster malvaceus*) are the chief associates of the oak and snowbrush. (Pl. 2, C.). This area is clearly a potential Douglas fir site, burned over after logging many years ago, as is indicated by the large stumps of this species found on the area.

The march of available soil moisture at a depth of 6 to 12 inches and that of daily precipitation on these two sites for the seasons of 1919 and 1920 are shown in Figure 18. Evaporation for the same seasons and soil temperature at a depth of 1 foot for the season of 1920 are shown in Figure 19. The soil moisture and evaporation data for these years are summarized in Table 10.

TABLE 10.—*Summaries of soil moisture and evaporation data on experimental planting areas, Big Cottonwood watershed, Wasatch National Forest, Utah, growing seasons of 1919 and 1920*

| Site | Depth of sample | Seasonal averages of total soil moisture | | | Wilting coefficient of soil [1] | Mean daily evaporation | | | $\frac{E}{SM}$ [2] |
|---|---|---|---|---|---|---|---|---|---|
| | | 1919 | 1920 | Average | | 1919 | 1920 | Average | |
| | *Inches* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *C. c.* | *C. c.* | *C. c.* | |
| Western aspect, snowbrush-oak | 0 to 6 | 7.4 | 10.1 | 8.8 | 10.9 | 33.46 | 18.65 | 26.06 | 2.86 |
| | 6 to 12 | 8.8 | 9.4 | 9.1 | | | | | |
| Average | | 8.1 | 9.8 | 9.0 | | | | | |
| Southern aspect, sagebrush-snowbrush-oak-aspen | 0 to 6 | 6.8 | 9.4 | 8.1 | 12.4 | 38.27 | 20.90 | 29.58 | 2.79 |
| | 6 to 12 | 9.6 | 11.7 | 10.6 | | | | | |
| Average | | 8.2 | 10.6 | 9.4 | | | | | |

[1] Determined in the biophysical laboratory, Bureau of Plant Industry, U. S. Department of Agriculture, by the Briggs and Shantz centrifugal method.

[2] Mean daily evaporation divided by the mean seasonal total moisture content of the soil at a depth of 6 to 12 inches.

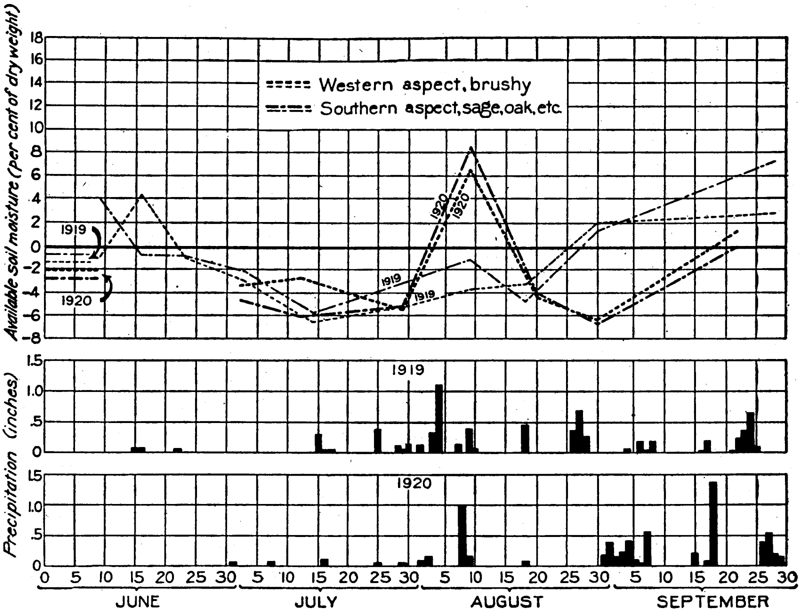



**Figure 18.**—March of available soil moisture at depth of 6 to 12 inches and daily precipitation, Big Cottonwood watershed, central Utah, seasons of 1919 and 1920. (Seasonal averages shown by horizontal lines at left of graph)

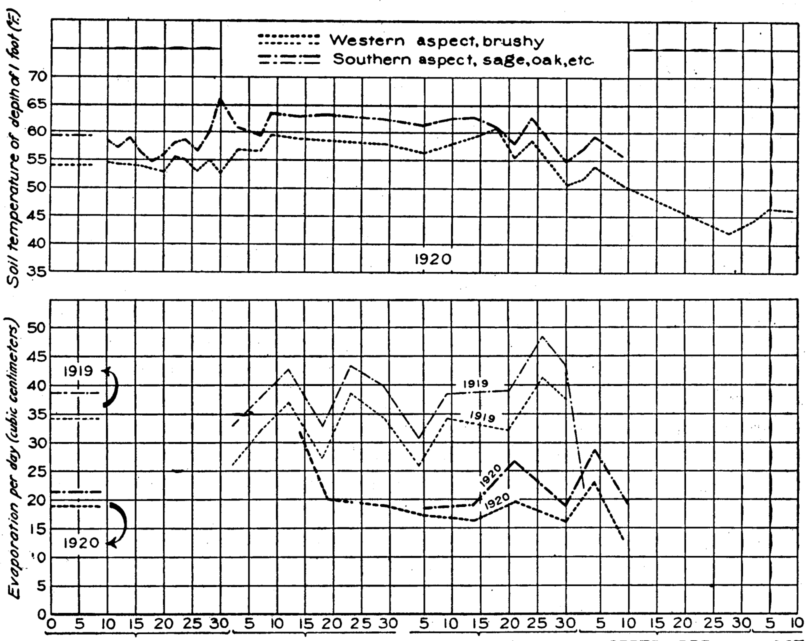



**Figure 19.**—March of evaporation for seasons of 1919 and 1920, and of soil temperature at a depth of 1 foot for season of 1920, Big Cottonwood watershed, central Utah. (Seasonal averages shown by horizontal lines at left of graph)

As compared with that in Ephraim Canyon, the average content of available moisture in the upper layer of soil in Big Cottonwood Canyon is somewhat less during the growing season; in 1919 the evaporation was virtually the same, and the ratio $\frac{E}{SM}$ is therefore higher for the Big Cottonwood area. On the latter the vegetation is on the whole much denser than on the Ephraim Canyon watershed, which may explain the lower moisture content of the soil; this is especially true of the upper soil layer on the south aspect, where the sagebrush is sufficiently abundant to exhaust quite effectively the supply of available soil moisture. Although soil moisture is somewhat lower in Big Cottonwood Canyon than in Ephraim Canyon, the soil is more fertile, better aerated, and of much lighter texture; it is undoubtedly suitable in texture for western yellow pine.

Survival on the Big Cottonwood Canyon sites is somewhat better than that on the Ephraim Canyon watershed, although the irregularity of the results on the former areas prevents any sharp comparison. The first plantation established in Big Cottonwood Canyon, in the fall of 1913, was remarkably successful, but the others, such as that of the fall of 1919, were very poor. Spring plantings with 2–1 western yellow pine, however, survived about as well as those obtained on the Ephraim Canyon squaw-apple site; in Big Cottonwood Canyon sagebrush-snowbrush-oak-aspen an average of 71 per cent of the trees was alive after one year, and the survival on the Ephraim Canyon squaw-apple site was 72 per cent.

In rate of growth and percentage of vigorous trees, as well as in survival, the results in Big Cottonwood Canyon are satisfactory, considering the damage by snowshoe rabbits to which the plantations have been subjected (*3*). The oldest plot for which records of both survival and height growth are available was planted in the fall of 1913 on the south-facing slope. In 1918 this plot showed a survival of 66 per cent, and the trees averaged 13 inches in height. A 7-acre plantation (not shown in Table 9) made at the same time on a similar but less rocky site on the same southern slope had about the same survival, but the plants attained an average height of slightly more than 22 inches in 1918 and were growing at an average rate of 3.5 inches a year.

From the height growth of the trees in the older plantations that are free from snowshoe-rabbit injury, it is evident that the growth of the Big Cottonwood plantations after they have become established will exceed the rate of height growth of the Ephraim Canyon plantations. This is doubtless due to the light texture, the open and porous structure, and the greater fertility of the Big Cottonwood Canyon soil, together with better soil moisture at greater depths,[8] as indicated by the presence of aspen and mesophytic shrubs on the areas.

The western-aspect brush site planted in Big Cottonwood Canyon had a lower average survival than the southern-aspect site. The physical characteristics of the two sites are similar; available soil moisture, taking both years of observation into consideration, is al-

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[8] The western yellow pine transplants on these sites have, no doubt, been able to obtain moisture from below the 12-inch level. This tends to explain their survival during the protracted dry period in 1919 when the available moisture in the 6 to 12 inch layer was exhausted early in the summer. Figure 18.

most identical; but on the site with western aspect evaporation is less intense than on that with southern. The real cause for the apparently poorer showing on this site is that there is no exceptionally good plantation, like that of the fall of 1913 on the southern-aspect site, to raise the average. Comparing results obtained the same year, it is seen that the western-aspect site has shown better results three times, poorer results once, and the two sites have shown virtually the same results three times, indicating that the site with western aspect is really slightly better than that with southern. This is probably due to lower evaporation and to a coarser, more favorable soil, as shown by the lower wilting coefficient.

The heavier precipitation in Big Cottonwood Canyon than in Ephraim Canyon should not be overlooked. The plots planted in 1919 and 1920 show very plainly that the success of western yellow pine planting on either of the Big Cottonwood Canyon sites depends largely on the depth of rainfall during the first growing season following planting. The season of 1919 was unusually dry, and consequently the mortality of the trees planted that spring ranged from 47 to 88 per cent. On the other hand, the season of 1920 was more favorable in moisture supply, and on the four plots planted that spring the mortality ranged only from 8 to 15 per cent.

### BEAVER CREEK WATERSHED, WASATCH NATIONAL FOREST

As in Big Cottonwood Canyon, the survival of the pine on the Beaver Creek watershed was also somewhat better than in Ephraim Canyon. As indicated by the type of vegetation, this was due to a cooler climate and greater soil moisture, and to a somewhat more porous and less calcareous soil—a rocky silty fine sandy loam.[9]

The results of plantations on this watershed are given in Table 9. As might be expected under these circumstances, the difference between the cleared and uncleared sagebrush plots was not quite so striking as on the Ephraim Canyon watershed, although still decisively in favor of the cleared areas. As with the Ephraim Canyon results, the difference is undoubtedly attributable to the root competition between the sagebrush and the pine for the supply of available soil moisture, which reaches a minimum during the active growing season.

### MINK CREEK WATERSHED, CACHE NATIONAL FOREST, IDAHO

As a further check on the Utah results, those obtained on the Mink Creek watershed of the Cache National Forest in southern Idaho are of interest. On this watershed four different sites were planted with western yellow pine in 1917, as follows: (1) A sagebrush area, burned over in the fall of 1915, on which sage was coming in quite vigorously and on which a rank growth of sticky geranium (*Geranium viscosissimum*) had come up; (2) a site with a southwestern aspect on which sagebrush and spineless horsebrush (*Tetradymia canescens inermis*) were dominant; (3) a site with northeastern aspect on which bitterbrush (*Purshia tridentata*) and snow-

[9] One of the most northern natural occurrences of *Pinus scopulorum* in Utah is found on the Beaver Creek watershed near the planting area, and lodgepole pine occurs naturally in this locality. The oak brush on this watershed is not so dense and tall as it is on the Manti National Forest.

berry dominated, but which was burned over in 1915 and was again sprouting up to the same species; and (4) an unburned brushy northeastern-aspect site on which snowbrush, serviceberry, myrtle boxleaf (*Pachistima myrsinites*), bitterbrush, chokecherry, wild rose (*Rosa oreophila*), and snowberry are associated in a very dense stand—an impenetrable thicket in places. These areas lie between 5,500 and 6,000 feet in elevation. The sagebrush area, also, was planted in 1916 and in the spring of 1915 an aspen area was planted but was burned over the same fall. The records of these plantations are summarized in Table 11.

TABLE 11.—*Record of experimental plantations of 2-1 western yellow pine on the Mink Creek watershed, Cache National Forest, Idaho*

| Site | Date planted | Survival | | | | Vigorous trees last examination in per cent of total number |
|---|---|---|---|---|---|---|
| | | First year | Second year | Third year | Fourth year | |
| | | Per cent | Per cent | Per cent | Per cent | Per cent |
| Sagebrush flat | Apr. 24, 1916 | 61.5 | 54 | ------- | ------- | 28.5 |
| Do | Apr. 27, 1916 | 36 | 19.5 | ------- | 11.0 | 2 |
| Do | do | 80 | 56 | ------- | 25.5 | 7 |
| Do | do | 57.5 | 40.5 | ------- | 14.5 | 2 |
| Do | do | 69 | 50 | ------- | 22.5 | 2 |
| Do | Apr. 26, 1916 | 58 | 26 | ------- | ------- | 21 |
| Do | May 15, 1917 | 0 | ------- | ------- | ------- | 0 |
| Do | do | 7 | ------- | 0 | ------- | 0 |
| Do | May 18, 1917 | 16 | ------- | 0 | ------- | 0 |
| Do | do | 35 | ------- | 0 | ------- | 0 |
| Southwestern aspect, sagebrush-horsebrush | May 17, 1917 | 7 | ------- | 1 | ------- | 0 |
| Do | do | 61 | ------- | 8 | ------- | 0 |
| Northeastern aspect (brushy, burned over) | do | 91.7 | ------- | 1 | ------- | 1 |
| Do | do | 47 | ------- | 7 | ------- | 2 |
| Aspen cove (very gentle slope to north) | Apr. 15, 1915 | 67 | (1) | ------- | ------- | 14 |
| Northeastern aspect (brushy, unburned) | May 16, 1917 | 88 | ------- | 81 | [2] 78 | 68 |
| Do | May 21, 1917 | 91 | ------- | 81 | [3] 78 | 74 |
| Do | Apr. 26, 1918 | ------- | 75 | [4] 66 | ------- | 56 |

[1] Burned over autumn of 1915.
[2] Average height growth last year observed 1.3 inches.
[3] Average height growth last year observed 1.2 inches.
[4] Average height growth last year observed 1.8 inches.

These areas receive about 12 inches of rainfall during the growing season. The days are warm, and the nights are cool, only two and a half months being free from killing frosts. The soil on the planting areas is derived from schist, diorite porphyry, limestone, and quartzite, and ranges from a rather heavy brown silt loam on the sagebrush site to a gray to black silty very fine sandy loam on the other areas. It is not excessively calcareous.

The march of soil moisture and evaporation was determined for the season of 1917, the former being shown in Figure 20 and the latter in Figure 21. The average total moisture content of the soil and the average evaporation intensities for the season are given in Table 12. The moisture content of the upper soil layer is below the wilting coefficient on these sites during the most critical part of the growing season, and even the seasonal averages fall below the wilting coefficients. The evaporation rate of the southwestern aspect exceeds that on any of the Ephraim Canyon sites under investigation in 1917,

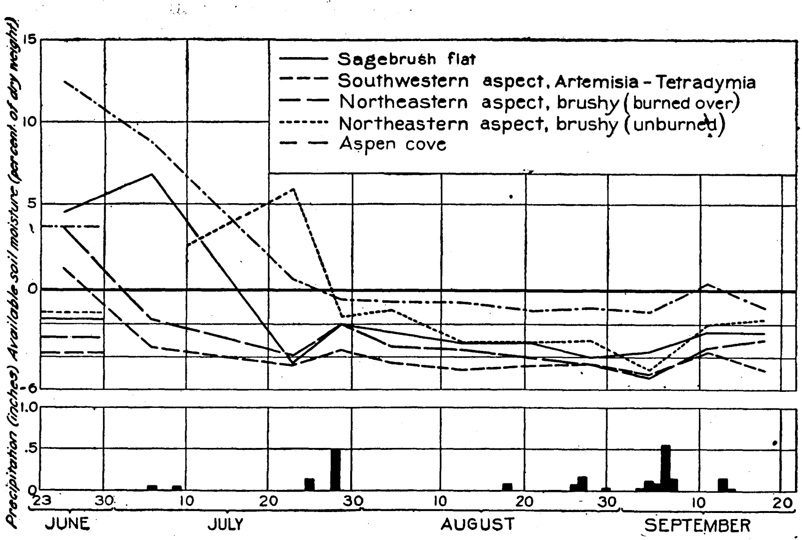


**FIGURE 20.**—March of available soil moisture at depth of 6 to 12 inches and daily precipitation, Mink Creek watershed, Cache National Forest, southern Idaho, season of 1917. (Seasonal averages shown by horizontal lines at left of graph)

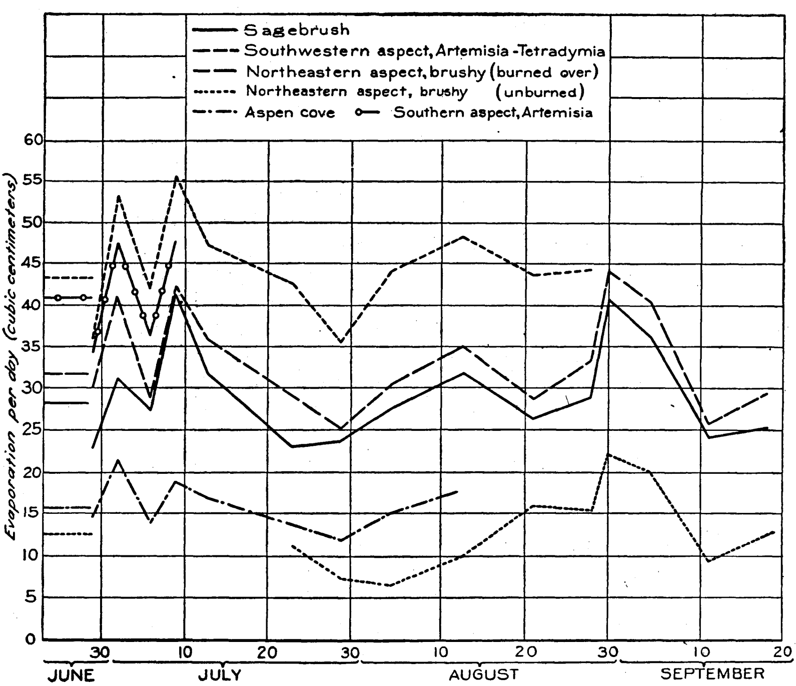


**FIGURE 21.**—March of evaporation, Mink Creek watershed, Cache National Forest, southern Idaho, season of 1917. (Seasonal averages shown by horizontal lines at left of graph)

but the unburned brush-covered northeastern aspect had a much lower evaporation intensity than any of the other sites planted on this or any of the other watersheds.

TABLE 12.—*Soil-moisture and evaporation data on experimental planting areas, Mink Creek watershed, Cache National Forest, Idaho, growing season of 1917*

| Site | Depth of sample | Seasonal average of total soil moisture | Wilting coefficient [1] | Mean daily evaporation | $\frac{E}{SM}$ [2] |
|---|---|---|---|---|---|
| | *Inches* | *Per cent* | *Per cent* | *C. c.* | |
| Sagebrush, flat | 0 to 6 | 8.8 | 11.8 | 28.14 | 2.76 |
| | 6 to 12 | 10.2 | | | |
| Average | | 9.5 | | | |
| Southwestern aspect, sagebrush—horsebrush | 0 to 6 | 6.7 | 10.4 | 43.38 | 6.67 |
| | 6 to 12 | 6.5 | | | |
| Average | | 6.6 | | | |
| Northeastern aspect, brushy (burned over) | 0 to 6 | 10.6 | 13.2 | 31.78 | 3.09 |
| | 6 to 12 | 10.3 | | | |
| Average | | 10.4 | | | |
| Aspen cove (very gentle slope to north) | 0 to 6 | 12.8 | 10.4 | 15.45 | 1.31 |
| | 6 to 12 | 11.8 | | | |
| Average | | 12.3 | | | |
| Northeastern aspect, brushy (unburned) | 0 to 6 | 11.6 | 13.6 | 15.35 | 1.25 |
| | 6 to 12 | 12.3 | | | |
| Average | | 12.0 | | | |

[1] Determined in the biophysical laboratory, Bureau of Plant Industry, U. S. Department of Agriculture, by the Briggs and Shantz centrifugal method.
[2] Evaporation divided by the mean seasonal total moisture content of the soil at a depth of 6 to 12 inches.

The planting resulted in almost complete failure on all the sites except the aspen site and the brush site with northeastern aspect. No examination was made of the plantation on the aspen site after the first year. On the other site the plantations were very successful. (Table 11.) Two of these plantations made in 1917 each had 78 per cent alive at the end of the fourth growing season, of which 68 and 74 per cent, respectively, of the total number planted were vigorous. Much higher survivals were obtained with western yellow pine on this site than on any other area in the entire intermountain region.

This brushy northeastern slope is regarded as being a potential Douglas fir site and, in fact, Douglas fir planted here made a good showing both as to survival and height growth. Snowshoe rabbit injury, to which the Ephraim Canyon and Big Cottonwood plantations are subject, does not occur on the Mink Creek watershed. As compared with the other Mink Creek sites, soil moisture is relatively high on this site, the wilting coefficient is highest, and evaporation and $\frac{E}{SM}$ are lowest. Although this site is covered with a very dense stand of brush, all the species, with the exception of snowberry, are deep rooted, so that root competition is probably not keen. The area is also well supplied, during the early part of the growing season, with both surface water and seepage from snowdrifts lying to the leeward of the crest of the ridge above the planting area. These drifts remain for some time after the snow has disappeared from the other slopes. The supply of moisture in the upper layer of soil, however, reaches the wilting coefficient during the middle of the growing season, but even then, on account of the protection which the site receives, the evaporation rate is very low, favoring higher survival.

The fact that the soil moisture on all the Mink Creek sites is below the wilting coefficient for a considerable period is further evidence that western yellow pine, although using considerable water when water is available, apparently reduces transpiration to almost nothing during time of drought.

The other sites on the Mink Creek watershed are much less favorable, being potential brush lands in which sagebrush and other drought-resistant shrubs occupy a prominent place. The topography of these sites is rolling, and the majority of them are therefore exposed to the full sweep of the prevailing winds, which come from the desert lying to the southwest. The dense growth of sagebrush makes heavy demands on the upper layer of soil for the little moisture it contains. As the moisture supply of the surface layer becomes exhausted and the native vegetation begins to draw its supply from lower levels, the pine trees, whose roots rarely reach a depth greater than 12 inches during the first growing season after planting, succumb. It is evident that on sites similar to these, on which sagebrush occurs as a dominant species, planting will result successfully only when moisture is plentiful, owing to unusually heavy rainfall during the first two or three years following planting. Seasons of scanty rainfall are disastrous on such sites. On the other hand, the planting of western yellow pine proves successful on protected sites or temporary brush-land areas similar to the potential Douglas fir site mentioned above, upon which the deep-rooted species predominate.

## MORE EXTENSIVE PLANTATIONS

The results on the experimental plantations have been further substantiated by those on a number of more extensive plantations also made by the Forest Service, United States Department of Agriculture (*29*). Among these may be mentioned the Salt Creek plantation on the Nebo division of the Uinta National Forest. Here western yellow pine planted in sagebrush and oak brush has succeeded very well on account of the favorable soil—a loose very fine sandy loam derived from sandstone—and a June and July rainfall considerably above normal in 1914, the year of establishment. In the sagebrush, where the soil is very fertile and light is of almost full intensity, the trees were 13.4 inches tall in 1918, and the current growth of the year was 3.8 inches. In the oak brush the height of the trees averaged 11.4 inches and they grew 2.6 inches in 1918; but the survival was obviously very much better.

Another successful plantation was made the same year in Ephraim Canyon in the lower oak-brush type, characterized by scattered clumps of low oak brush interspersed with mountain-mahogany. The heavy early summer rainfall was probably the chief factor in making this plantation a success, while many plantings made in similar situations in other years were failures. In the fall of 1920 these trees averaged 12.4 inches in height and made a current growth of 1.8 inches. They showed considerably poorer development than trees in the Salt Creek plantation, owing to the less favorable site, as reflected by the invasion of piñon pine.

Another successful plantation was made in oak brush and sagebrush in Oak Creek Canyon on the Fillmore National Forest[10] in 1915. Here, as on the Salt Creek watershed, the sagebrush site shows the best growth, the trees attaining a height of 16.0 inches in 1920, whereas in the oak brush the height was but 10.6 inches. The soil, a sandy loam derived from quartzite, has doubtless had a great bearing on the success of the plantation.

## CONCLUSIONS FROM STUDY OF PLANTATIONS

The results of all the plantations on the Ephraim Canyon, Big Cottonwood Canyon, Beaver Creek, and Mink Creek watersheds and elsewhere point to a lack of available soil moisture during the first season as the chief cause of the early failure of the plantations. This deficiency is characteristic wherever the brush types are permanent, and plantations will not be successful unless moisture is conserved by clearing off the established shallow-rooted vegetation that monopolizes the scanty water supplies upon which the newly planted trees must depend. As an alternative the plantation may be made under a moderately light cover of deep-rooted brush which by its partial shade reduces evaporation and transpiration and because of the absence of roots in the upper layers of soil affects surface moisture but little. Even under these conditions wholly satisfactory results are limited to years of exceptionally heavy summer rainfall.

Toward the upper limits of a brush-land zone areas of temporary brush occur. Their temporary nature is indicated by tree stumps, evidences of fire, or the presence of conifer types on areas obviously similar. In these places planting is much more successful. The moisture content of the soil in such places is much higher, and the species making up the brush are more mesophytic. Even in such places, however, the presence of shallow-rooted brush is a factor which clearly reduces success.

Although soil moisture is the chief factor controlling survival, it is evident that soil texture is also important, since a light porous soil increases the survival of the pine. Growth and vigor are likewise stimulated by the texture and fertility of the soil. Evaporation, because of its influence on available soil moisture and transpiration, is also a factor which influences survival.

The foregoing discussion applies chiefly to first-year losses. After the first year the surviving trees are not limited to the moisture supply at a depth of 6 to 12 inches and consequently are less susceptible to injury from drought in June and July. Although further mortality will take place, this will usually be at a diminishing rate, and each additional year will tend to establish the survivors more firmly.

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[10] Now a part of the Fishlake National Forest.

After the first year, shade may become a factor inducing high mortality in plantations originally showing excellent survival. The shade cast by a solid canopy of oak is disastrous, as is the shade of dense aspen or chokecherry. Where oak brush grows in isolated clumps, western yellow pines planted in the spaces between the clumps or on the north edge have a good survival and growth. Manzanita, sagebrush, snowbrush, low oak brush up to 3 feet in height, and other shrubs which do not form a closed canopy do not appreciably affect the development of western yellow pine by shading. Their root characteristics, which influence the rate of depletion of soil moisture, are much more significant.

The practical conclusion from these plantations is that pine planted in the obviously temporary brush types, particularly those characterized by a deep-rooted mesophytic vegetation, is most successful and that these lands should be planted first. Of the permanent brush sites considered in this study, areas cleared of sagebrush offer the best planting sites, especially if soil moisture is normally good, if evaporation is low, and if shallow-rooted herbs do not immediately invade the area.

The other brush-land sites have so many complex factors involved, such as soil moisture, evaporation, and shade, all of which are intricately interrelated, that simple rules for the selection of planting sites can not be formulated. There are, however, certain fundamental facts involving the moisture relations of the sites which can be determined by a study of the indicator significance of the native vegetation on the ground. An understanding of these clarifies the whole problem of the choice of planting sites in the permanent brush lands.

## NATIVE VEGETATION AS AN INDICATION OF THE SUITABILITY OF PLANTING SITES

In the preceding discussion it was shown that, of the various factors affecting the success or failure of planted western yellow pine, the competition of shallow-rooted vegetation is one of the most important. After the shock of transplanting, the drying out of the soil through transpiration of competing brush growth imposes a tax upon the recuperative powers of the young pine transplants that may result in heavy losses. The success or failure of plantations is evidently determined in large measure by the character of the root systems possessed by the competing vegetation. It should therefore be possible, from a knowledge of the water relations of the native plants and of their root systems in relation to different soil layers, to determine the conditions of vegetation under which the pine can be planted successfully. This suggests a more detailed study of the native vegetation to determine its significance as indicating the suitability of the brush-land sites for forest planting.

The use of plant indicators, or a method of assessing the growth value of certain lands by means of the natural growth found thereon, has been a factor in the settlement and development of new regions and is doubtless almost as old as agriculture itself. When the pioneers settled the great Ohio Valley, some of them selected land covered with sugar maple and beech. These were more prosperous than those who settled on oak and pine lands. Likewise in the Great Salt Lake Desert, those lands which were covered with a tall, luxuriant growth of sagebrush yielded the best agricultural crops when put under irrigation. While herbaceous plants have been used much less in judging the fertility and character of agricultural soil, many of them are quite as characteristic as the trees. Hilgard (*22*) made one of the first successful attempts to organize a system of indicator plants and thus to recognize a relationship of plants to soil based upon the response of the plant to its environment.

Shantz (*46*) has pointed out that the character of the native plant cover can be used as a reliable indicator of the capacity of land for the production of farm crops in the short-grass region of Colorado, provided the relation between the vegetation and the environment is correctly interpreted. Kearney and others (*23*) have gone still further in the scientific study of native vegetation in the Tooele Valley, Utah. They have shown that the character of the native vegetation affords a reliable index of the conditions favorable or unfavorable to the production of farm crops and have incidentally established correlations between the native plant cover and the available moisture and the physical and chemical properties of the soil.

Sampson (*44*) has studied the relationship between the native vegetation and the carrying capacity of range lands and has developed the practical application of these principles to a point where they are of great importance in the judicious management of the range lands in the western United States.

Clements (*16*) has treated extensively the fundamental concept of agricultural, grazing, and forest indicators in their broader ecological aspects.

European foresters, among whom Ratzeburg (*42*) and Ramann (*41*) may be mentioned, have long recognized the significance of characteristic indigenous forms of the lesser vegetation as indicators of site quality. Cajander (*9*) has recently treated the native vegetation of central and eastern Europe as indicators of site quality in the demarcation of forest types, and Frömbling (*17*) and Rubner (*43*) have still more recently emphasized the use of the lower forms of plant life in the forest as indicators in solving many of the difficult silvicultural problems of natural regeneration, thinnings, and methods of cutting.

In the United States no equally comprehensive studies have been made of plant indicators for forest production, although, scattered through the forestry literature, brief notes are found suggesting the possibility of a relation between natural vegetation and forest productivity.

As early as 1808, Peters (*39*), as a result of observations made in Northampton County, Pa., called attention to the fact that hemlock, white pine, and pitch pine are likely to be found on deep, fertile loams as well as on the thinnest, sterile sandy soils, and that therefore timber alone is not always an invariable indicator of the capabilities of the land. Some of the recent literature on the use of the native vegetation as indicators of forest sites has been reviewed by Korstian (*24*, *25*).

Every site is a complex of climatic and soil characteristics having a determining influence upon the character of the vegetation. Therefore, in the determination of site quality a detailed consideration of the individual causal factors is not essential if it can be assumed that their combined effect will be evident in the composition and vigor of the vegetation. The native plants, in their response to the site factors, presumably show the effect of the summation of these factors. Every plant may, therefore, be regarded as a criterion of the environment in which it grows and, moreover, an indicator of the behavior on the same site of other species whose requirements are known.

Studies of the natural successional relations of the native shrubby species, their root development, the relative size, structure, and moisture content of the leaf, sap density, and relative transpiration were therefore undertaken to determine, as far as possible, the significance of the native vegetation on the various sites.

## FAILURE OF SUCCESSIONAL STAGE AS AN INDICATOR

In the first of these studies an attempt was made to test a hypothesis, which, if confirmed, would simplify the choice of planting sites through the use of native vegetation. Since the planting of pine in the brush type appears to be merely the artificial forcing of a plant succession which takes place naturally under conditions not greatly dissimilar, a working hypothesis was built up upon this basis, using principles of plant succession already worked out for the general Rocky Mountain region, largely by Clements (*15*).

It is evident that where it occurs naturally in southern Utah and central Idaho western yellow pine is the climax forest. In both these regions, after fires or other accidents kill out the pine, a plant succession is started in which shrub associations similar to those characteristic of the intervening pineless belt occupy the areas until western yellow pine seeds in and again becomes dominant. Consequently the different associations within the brush-land zone would naturally appear to be favorable to western yellow pine in the order of their successional sequence. An attempt was therefore made to work out these successional relations as typified in the oak-brush zone in Ephraim Canyon.

The details of the earlier stages of the succession on wet lands are immaterial to this study, as swamps and bogs are not considered as planting sites for western yellow pine. As these areas dry up, however, they can be considered. According to the authors' observations, the bogs develop directly into typical sagebrush flats in which sedges (*Carex* spp.) may persist for some time. The sagebrush is aggressive and the change appears to occur rapidly and to be generally extensive. The next change, to oak brush, appears to be very slow, sometimes involving a temporary intermediate stage characterized by serviceberry. Acorns falling upon bare ground are killed by drying out or the alternate freezing and thawing to which they are subjected in the autumn. When covered by a layer of oak or serviceberry leaves they doubtless remain viable and many sprout and take root before the winter snows cover them. Hence in some cases the serviceberry favors the invasion of the oak. Once the oak brush gains a foothold it has no difficulty in shading out the sagebrush and in persisting as the climax type of vegetation.

The succession on dry lands is less easily followed than that on the wet lands on the opposite side of the oak-brush climax. Rocky ridges bear an open stand of shrub species that may consist of common mountain-mahogany, bitterbrush, squaw-apple, or manzanita, or mixtures of these species together with sporadic occurrences of serviceberry, winter fat, and possibly other shrubs. Manzanita tends to grow in pure stands more commonly than the others, occurring typically on the poorest soil, usually of sandstone origin. It perhaps should be placed one stage lower in successional sequence than its associates. Except on these rocky, thin-soiled ridge tops, the oak brush at once comes in, at first low in stature but clearly dominating the site as the climax type of vegetation.

Fire in the oak brush, as will be shown in the following section, causes only a very temporary change, since the brush sprouts vigorously the next year and soon regains its dominance. In the sagebrush, however, the effect of fire is more lasting and may lead to a prolonged occupation of the site by grasses and herbs, depending somewhat upon the size of the burn. On small burns the sagebrush will again be in full possession of the area within three years.

As soon as the main stages in the local plant succession were determined, as shown above, it was realized that the successional relations of the native vegetation offered no clue to the suitability of the different sites for the planting of western yellow pine. The experience with forest planting in the intermountain region has shown the validity of this conclusion. The chief reason appears to be that western yellow pine—as well as other species of pine—possesses many of the characteristics of plants growing in waste places. Open bare soil best fulfills its requirements for initial stages of growth, for there the pine finds the most favorable soil moisture as well as temperature. While it is probably true that as the succession progresses the soils themselves become increasingly favorable, yet the pine can not take full advantage of the changed site conditions so long as a natural vegetation, adapted to the minimum soil moisture for western yellow pine, remains on the ground to compete with the pine for the scanty water supplies.

Furthermore, root development in the upper soil layers, which is so important in determining soil moisture and the initial survival of western yellow pine plantations, does not vary regularly with the successional stages. The successional stage of the vegetation, therefore, can not be used as a means of determining the suitability of the site for the planting, so long as the trees are placed in competition with native vegetation equally drought enduring or more so. If the ground were cleared, as in agriculture, the results would obviously be very different, and use could probably be made of the successional stage as a general indicator of the suitability of the cleared site for western yellow pine.

In contradiction of the above conclusion that the so-called permanent brush lands have, for the most part, reached their climax type, it has been claimed that these brush lands represent a zone of successional immaturity caused by a retrogression following repeated fires in times prior to the advent of the white man. While this hypothesis is hardly tenable in view of the evidence already presented in regard to the essential climatic differences between the brush-land zone and the pinelands to the north and the south, nevertheless it may be well to point out briefly some of the other evidence that in part invalidates this contention.

Were this hypothesis true, dynamic successional changes would be general throughout the brush-land region, since it is no longer subject to repeated fires. A careful study of successional relations in the brush zone reveals that the major formations are now static, each occupying its own peculiar soil type. Sagebrush is a possible exception, as it seems to be open to extremely slow invasions of oak brush and aspen through extension by root suckers. Furthermore, while there is a scattering of conifers—Douglas fir and white fir—in most of the oak-brush zone, a careful study on the Ephraim Canyon watershed indicates that the effect is not cumulative. Scattered seedlings gain a foothold only about as fast as the mature trees die, so that there is no transformation of types but merely an uncertain, fluctuating, scattered occurrence of various conifers within the oak brush. Table 13 shows this clearly. Were a successful invasion occurring at the present time, seedlings and saplings would greatly outnumber the mature trees. The various scattered occurrences of western yellow pine well into the general pineless zone show no activity in extending themselves beyond present boundaries and merely maintain a precarious existence upon areas where particularly favorable soil and moisture conditions are found. There is accordingly no evidence that the brush lands here are maintained by fires alone.

TABLE 13.—*Scattered occurrence of conifer seedlings on north and south exposures in Ephraim Canyon, in trees per acre*[1]

| Aspect and tree species | Seedlings under 3 feet in height | Saplings 3 feet high to 4 inches d. b. h. | Small poles 4 to 8 inches d. b. h. | Large poles 8 to 12 inches d. b. h. |
|---|---|---|---|---|
| North slope: | *Number* | *Number* | *Number* | *Number* |
| Douglas fir | | 1.7 | 0.3 | 0.7 |
| White fir | 1.7 | 6.7 | 2.0 | .7 |
| Alpine fir | | .3 | | |
| Rocky Mountain red cedar | 4.3 | 5.7 | 1.0 | |
| Total | 6.0 | 14.4 | 3.3 | 1.4 |
| South slope: | | | | |
| Piñon | 1.5 | 2.5 | .5 | |
| Utah juniper | 2.0 | 1.5 | 6.5 | |
| Total | 3.5 | 4.0 | 7.0 | |

[1] Data obtained by a strip survey; no trees larger than 12 inches in dimaeter were present.

Furthermore, where fires have run, as in parts of the Douglas fir and spruce zones, the conifers become limited to areas marked by rocky outcrops and cliffs, where the ground cover is so broken that the light fires characteristic of the region can not spread. In the brush-land zone the sporadic occurrences of western yellow pine are confined to sandy soil or stream bottoms and are not free from forest fires.

The hypothesis that fire alone is responsible for the brush lands therefore has no basis. Moreover, there is no evidence in support of the hypothesis that the brush lands constitute a zone of successional immaturity resulting from repeated fires in the past.

## INDICATOR SIGNIFICANCE OF BRUSH-LAND SHRUBS BASED ON ROOT DEVELOPMENT

Root competition has already been referred to as one of the reasons why the establishment of western yellow pine within the brush lands is difficult. A direct study of root development for the purpose of throwing additional light on the suitability of the brush-land sites for forest planting was therefore desirable. Investigations in Utah (*23*) and in the short-grass regions of Colorado (*46*) have proved this to be a fertile field for determining the potentialities of agricultural lands.

Excavation of root systems of western shrubs has also been carried on by Cannon (*11*), Markle (*35*), and Weaver (*52*, *54*), but they did not make specific application of their results to any particular forestry problem. Weaver (*54*, *55*), however, has shown that root position clearly reflects soil moisture, especially when interpreted in its habitat relations, and that a study of root habit greatly facilitates the determination of the value of various species in indicating the potential productivity of agricultural and forest land. These studies, however, contain few data directly applicable to the present investigation, since entirely different species are treated. Moreover, the forester's problem is different from that of the farmer, since in forest planting the trees are placed in direct competition with the roots of the native vegetation, whereas in agriculture the ground is first prepared by plowing and all vegetation is removed. Thus the different types of root systems may have generally opposite indications in the two lines of investigation.

Roots extending to moderate depths indicate that the layers of soil that would be used by crop plants are periodically moist, and thus they are favorable indicators to the farmer who plows that vegetation under and plants his crop in the moist soil. To the forester, shallow roots indicate a maximum of root competition. The question at once arises whether a dry site free from shallow roots is inferior to a moist site crowded with shallow roots. The conclusion to be drawn from these studies of root systems, coupled with soil-moisture determinations and the results of plantations is that shallow-root competition, at least during the first year, is actually worse than a naturally dry site. A deep-soiled, moist flat covered with sagebrush having a very extensively developed superficial root system actually produced a lower initial survival of western yellow pine than the squaw-apple association on a hot, barren south slope where all the native vegetation draws its moisture from deep soil layers.

It is probable that in every association, except on some of the wettest sites such as marshes and stream banks, the native vegetation uses practically all the available water and that at the time of the summer minimum there is little water available anywhere. The best forest-planting sites would naturally be moist areas covered with deep-rooted vegetation. But these sites are equally suited to the invasion of shallow-rooted plants, and accordingly such ideal sites are rarely found. For example, what appeared to be a fairly moist slope occupied by common mountain-mahogany and serviceberry, both deep-rooted species, was planted to western yellow pine, with very poor results. Further study of the site revealed great quantities of snowberry of small size growing about the bases of the brush clumps, the well-developed, widespreading, shallow root systems undoubtedly making the area a poor planting site. A delicate relationship must, therefore, exist between the natural moisture of the site and the completeness of its removal by the vegetation upon it. Root habit can be used in only a broad way, with the main fact in mind that shallow-rooted vegetation is very unfavorable.

On the other hand, when this vegetation is removed by fire, overgrazing, or even plowing, pine can be planted with much better results, since it must then compete only with scattered or chance early invaders of the site rather than with a completely established ground cover of shallow-rooted species. Heavy grazing may help to produce favorable conditions by bringing about the destruction of shallow-rooted grasses and herbs, in much the same way in which it aids natural reproduction of western yellow pine in the Southwest (*37*).

To determine the root characteristics of the typical brush-land shrubs, a large number of root systems were excavated in Ephraim Canyon and at the pines station, an area within the natural western yellow pine type of the Manti National Forest, and in Big Cottonwood Canyon in the Wasatch National Forest, all in Utah. In most of the root systems excavated in this study, more attention was given to the general form of growth and development and the presence of feeding rootlets in the upper soil layers than to the greatest depth to which the roots penetrated. This was partly because the maximum depth of penetration was not pertinent to the study and partly because the heavy clay soil, which becomes dry and compact in midsummer, makes it exceedingly difficult to excavate root systems to any great depth without breaking off the small, brittle rootlets.

## CLASSIFICATION OF ROOT SYSTEMS AND THEIR SIGNIFICANCE

The root systems studied may be conveniently divided into four classes, each reacting upon the upper soil layer to a different degree, as follows: (1) Deep systems consisting mostly of taproots which spread in the lower layers of soil and have practically no feeding roots in the upper layers; (2) systems with widespreading rhizomes consisting of a shallow network of roots which are largely rhizomes and have only a few short feeding rootlets, coupled with a deep-feeding root system; (3) generalized systems consisting of many spreading roots feeding in upper and lower soil layers; (4) 2-storied systems consisting of shallow-feeding roots in the upper soil layers coupled with a very deep feeding root system, with practically no feeders in the intermediate soil layers.

### Deep-Rooted Species

To the first of these four classes belong the squaw-apple, rubber rabbit brush (fig. 22), bitterbrush (fig. 23), joint fir or Mormon tea (fig. 24), serviceberry (fig. 25), common mountain-mahogany (fig. 22), and sticky currant (fig. 26).

Of these, the rubber rabbit brush presents the most striking example of a deep-feeding root system. Each plant has one or a few long unbranched taproots supplied with only a few short hairlike rootlets for the entire length. No specimen was excavated to a sufficient depth to find where branching occurred, although one system was traced to a depth of 7 feet.

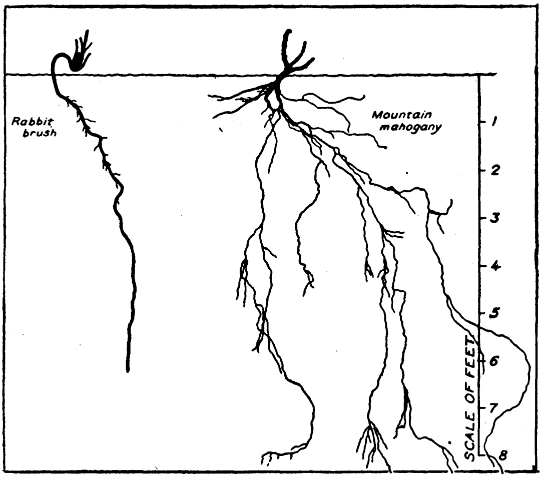



FIGURE 22.—Typical root systems of rubber rabbit brush (*Chrysothamnus nauseosus*) and common mountain-mahogany (*Cercocarpus montanus*) in oak-brush zone

Bitterbrush has somewhat the same type of root system but branches within a foot or two of the surface of the ground. The larger roots are covered with a dry stringy bark similar to that of cedar. Squaw-apple, joint fir, common mountain - mahogany, and serviceberry have systems which are very similar. There may be one or several taproots from the base of a medium-sized bush. These extend almost straight down, spreading only slightly and subdividing at intervals into somewhat smaller roots. All of the absorbing rootlets, however, lie at great depths in the soil, and practically none were found in these investigations.

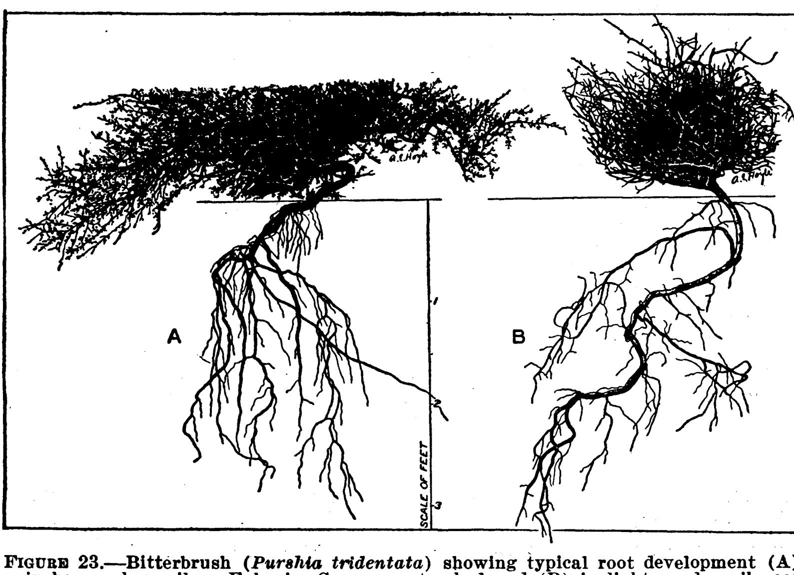



FIGURE 23.—Bitterbrush (*Purshia tridentata*) showing typical root development (A) in heavy clay soil on Ephraim Canyon watershed and (B) in light sandy soil near the pines station

Sticky currant (fig. 26) had very few feeding rootlets on any portion of the system excavated. The plant which was dug up had a root system 18 to 24 inches in lateral extension and between 3 and

4 feet deep. The relatively few branches on this system were quite long and had a few fibrous rootlets.

Serviceberry probably feeds at the shallowest depth of all the deep-rooted species, but even in this species the root system lies from 3 to 6 feet below the surface of the ground and naturally has very little effect upon planted western yellow pine. This type of root system obviously indicates highly favorable conditions for planting, as practically all root competition is absent. The presence of deep-rooted shrubs can in no way ameliorate a site that is already hot, dry, and consequently severe; their significance is that they do not render a good site unsuitable. Nearly all these shrubs are quite drought resistant and are characteristically found on severe sites. Bitterbrush and common mountain-mahogany, however, sometimes extend to sites that are only moderately severe, and common serviceberry and sticky currant are frequently found on mesophytic sites, the latter often in the temporary brush types on potential Douglas fir sites.

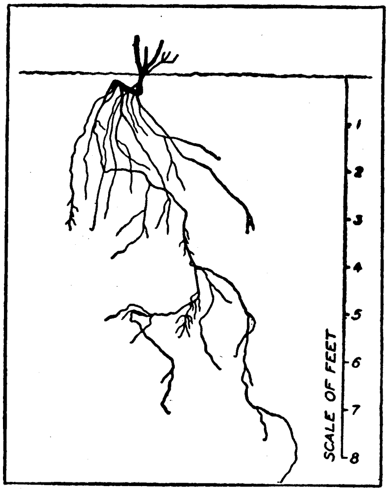



FIGURE 24.—Typical root system of joint fir (*Ephedra viridis*), often known as Mormon tea, in oak-brush zone

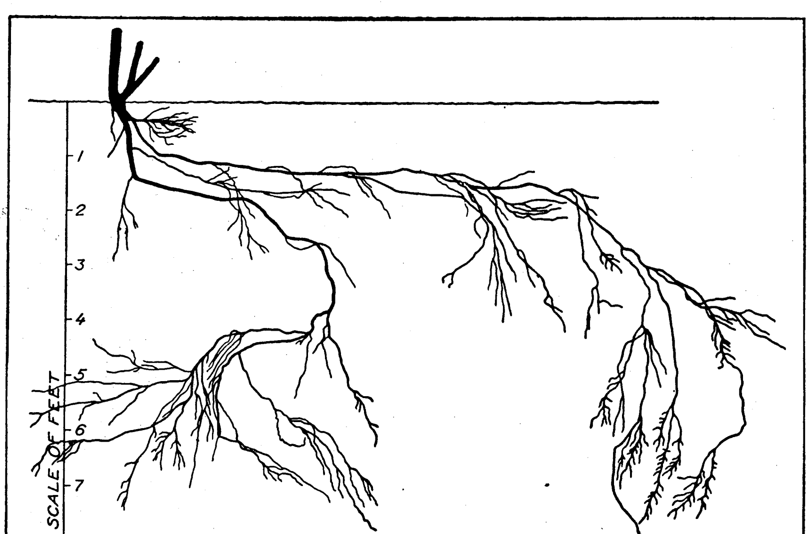



FIGURE 25.—Typical root system of common serviceberry (*Amelanchier alnifolia*) in oak-brush zone

Squaw-apple, rubber rabbit brush, and joint fir (Mormon tea) are almost always limited to such severe hot, dry sites that plantations on these sites will not succeed even if root competition is eliminated.

### SYSTEMS WITH WIDESPREADING RHIZOMES

In the second class of root systems are found those of oak brush (fig. 27, A), black chokecherry (fig. 28), Fendler rose (fig. 29), creeping hollygrape, winter fat (fig. 30), myrtle boxleaf (fig. 27, B), mallow ninebark (fig. 31), western thimbleberry (fig. 32), and bearberry honeysuckle (fig. 33).

All these species are characterized by the presence of rhizomes, generally bearing scanty feeding rootlets coupled with a more or less deep-feeding root system. It is obvious that the value of these plants as indicators is somewhat variable, depending upon the extent to which shallow-feeding rootlets are developed upon the rhizome.

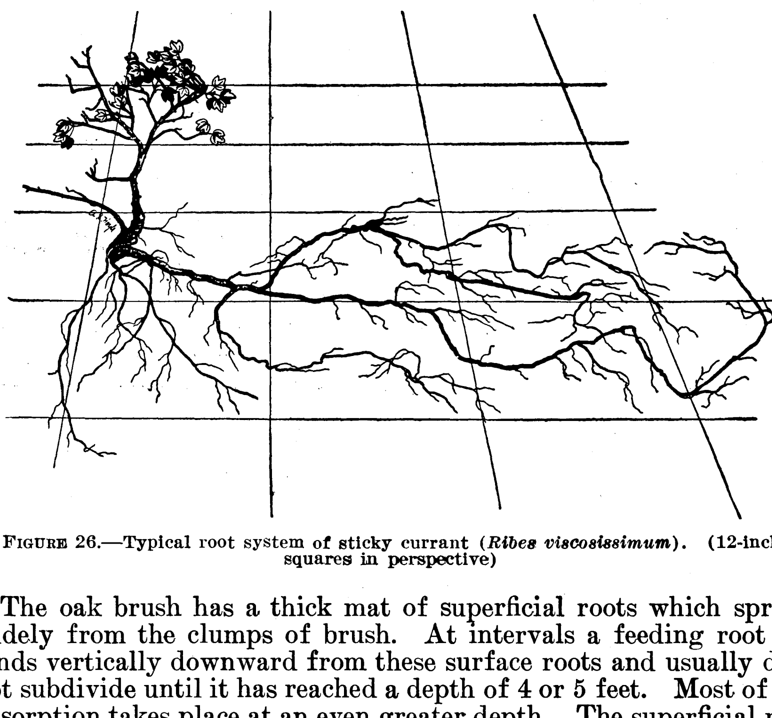


FIGURE 26.—Typical root system of sticky currant (*Ribes viscosissimum*). (12-inch squares in perspective)

The oak brush has a thick mat of superficial roots which spread widely from the clumps of brush. At intervals a feeding root extends vertically downward from these surface roots and usually does not subdivide until it has reached a depth of 4 or 5 feet. Most of the absorption takes place at an even greater depth. The superficial root system, although very highly developed, consists mostly of rhizomes, and there are few feeding rootlets in the upper foot of soil. The rhizomes make planting difficult in dense oak brush, as they interfere with digging the planting holes and with packing the soil firmly around the planted trees. Their interference with planting is probably more objectionable than the withdrawal of moisture from the soil after the tree is planted. While the oak-brush roots do not greatly impair the value of a planting site, in some places the brush is so luxuriant that good sites are unsuitable for pine because of the deficiency of light.

Black chokecherry has a root system similar to that of the oak but with fewer surface roots and less rhizome branching. Each bush has a few rhizomes extending in various directions, from which feeding roots extend straight downward for long distances, without branch-

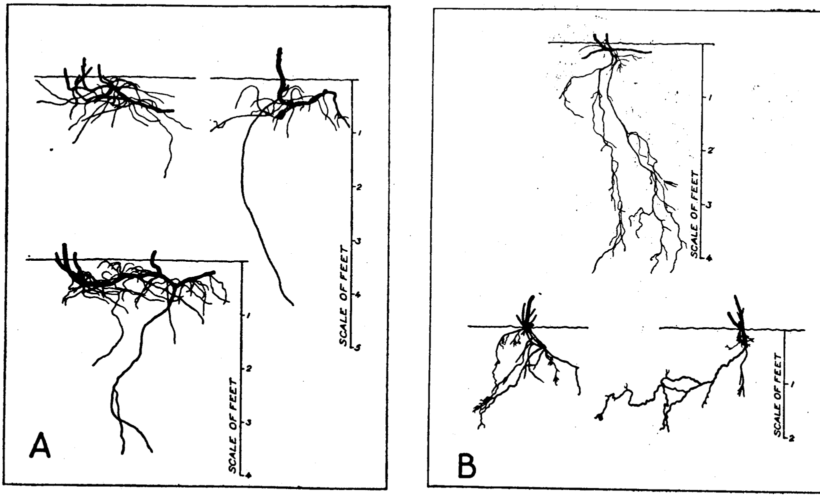



FIGURE 27.—*A*, Typical root systems of oak brush (*Quercus utahensis*) in Ephraim Canyon; *B*, Typical root systems of myrtle boxleaf (*Pachistima myrsinites*) in Ephraim Canyon

ing. Black chokecherry is confined to mesophytic sites, and since its root system is favorable, it is an indicator of high value and at its upper elevations may even indicate Douglas fir sites.

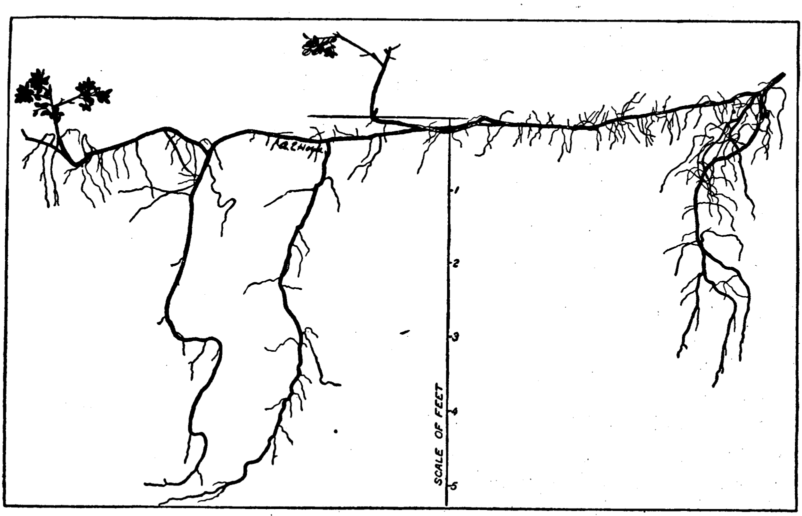



FIGURE 28.—Black chokecherry (*Prunus melanocarpa*) showing typical form of root system in oak-brush zone

The creeping hollygrape (*Odostemon repens*) root system is somewhat similar to that of the black chokecherry. About a foot below the soil surface a single rhizome generally occurs from which vertical feeding roots and shoots are sent out at intervals. The rhizomes are provided with a number of small feeding rootlets, but they are all very short and can withdraw water from limited areas of soil only. This species seldom dominates an area and usually must be considered in conjunction with other shrubs. It is frequently found on severe sites.

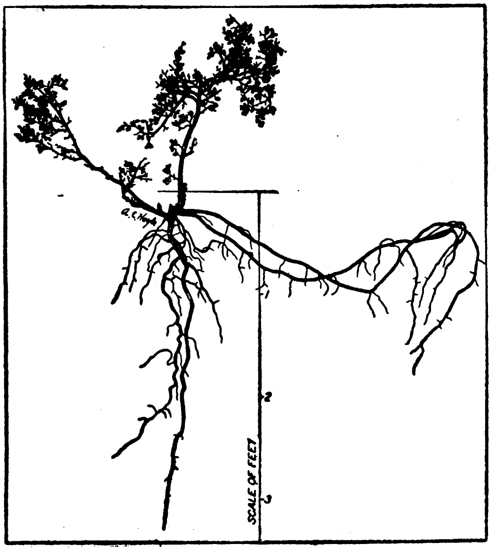



FIGURE 29.—Fendler rose (*Rosa fendleri*) showing typical root system in oak-brush zone

Winter fat occurs on dry sites which are generally unsuitable for planting. The root system is essentially deep feeding, consisting of main roots, running downward to great depths, that start at irregular intervals from a long rhizome 4 to 5 inches below the surface. This rhizome bears a few scattered roots which draw small quantities of water

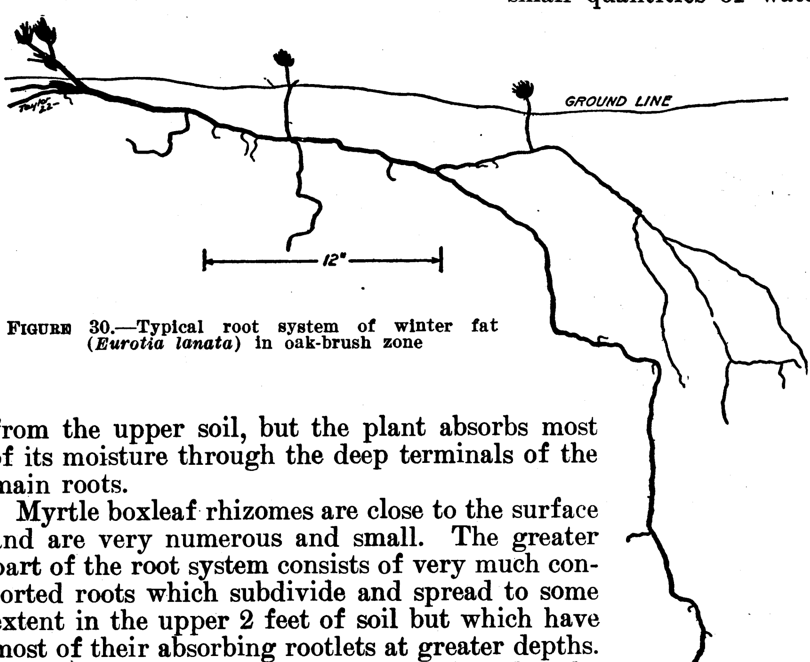



FIGURE 30.—Typical root system of winter fat (*Eurotia lanata*) in oak-brush zone

from the upper soil, but the plant absorbs most of its moisture through the deep terminals of the main roots.

Myrtle boxleaf rhizomes are close to the surface and are very numerous and small. The greater part of the root system consists of very much contorted roots which subdivide and spread to some extent in the upper 2 feet of soil but which have most of their absorbing rootlets at greater depths. This species is almost always found under the shade of aspen, oak, and other brush and is therefore not of primary importance as an indicator, although sometimes it occupies old Douglas fir burns to the exclusion of almost all other

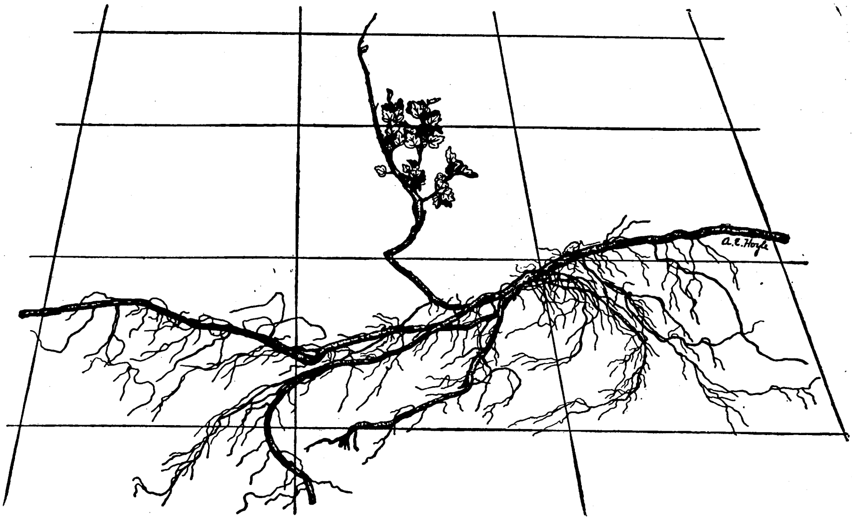


FIGURE 31.—Typical rhizomes and root system of mallow ninebark (*Opulaster malvaceus*). (12-inch squares in perspective)

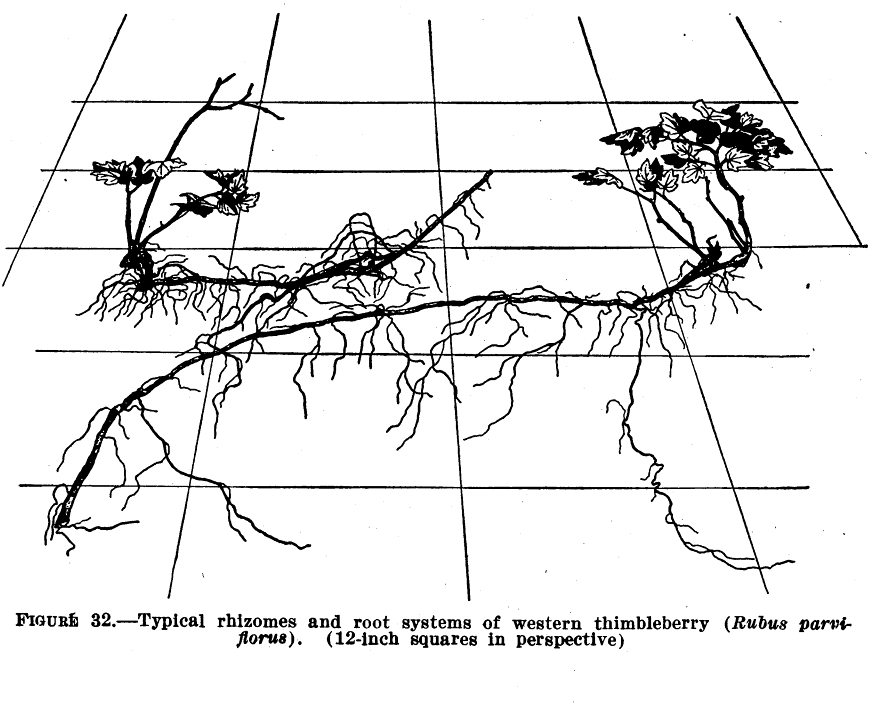


FIGURE 32.—Typical rhizomes and root systems of western thimbleberry (*Rubus parviflorus*). (12-inch squares in perspective)

vegetation. Its presence in association with other species in no way depreciates the indicator value of the major species.

The Fendler rose sends a taproot downward early in its life and later develops a more spreading root system, although at a considerable depth in the soil. Few feeding rootlets are found above the depth of 3 feet, except in young plants and on moist soils. After this root system is developed, the plants send out a few rhizomes in all directions, and these may in turn send down feeding roots to deeper levels and from time to time these rhizomes give rise to new rose plants along their lengths. Fendler rose occupies fairly well watered sites and consequently is an indicator of favorable sites; however, it rarely dominates an area, and its indicator value may have to be discounted because of less favorable associates.

Mallow ninebark has a rhizome running through the upper 12 to 18 inches of soil with a few small rootlets extending to a depth of 30

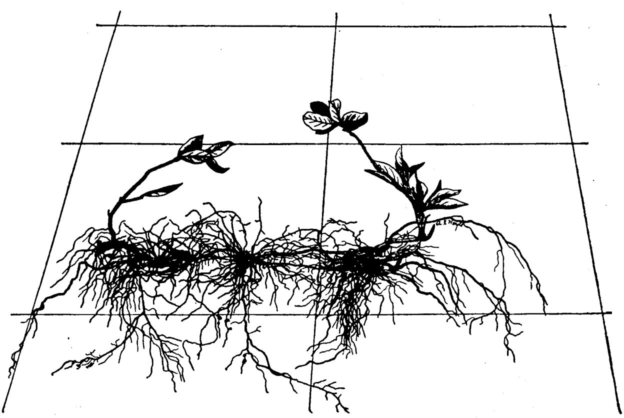


FIGURE 33.—Rhizomes and root systems of bearberry honeysuckle (*Lonicera involucrata*). (12-inch squares in perspective)

to 36 inches below the surface. It has many absorbing rootlets along the rhizome between plants. This species is not common in the brush zone but in Utah is more characteristic of temporary brush areas in the Douglas fir zone. However, in central Idaho it is frequently found on potential western yellow pine sites. The root system probably draws more heavily upon surface moisture than in the preceding species, but as it is generally found on moister sites the unfavorableness of the root system is largely offset. Mallow ninebark may therefore be regarded as an indicator of fair conditions for planting western yellow pine, either upon Douglas fir burns or permanent brush sites.

Western thimbleberry has a long rhizome running parallel to the surface of the ground at a depth of approximately 12 inches for 2 or 3 feet and then extending downward to a depth of 6 or more feet. Practically all the absorbing rootlets are found along the main root running parallel to the surface of the ground. This root system is of a still more unfavorable type. The plant is characteristic of moist

Douglas fir sites in Utah and is rarely found on the drier sites which would generally be chosen for pine plantings. Moreover, if planted on sites where thimbleberry occurs in dense stands, the heavy cover formed by the broad leaves of this shrub soon shades out the pine.

The bearberry honeysuckle has a root system composed of compact bunches of roots developed at close intervals, on a running rootstock. Each plant has a lateral extension of about 12 inches and a downward extension of 12 to 18 inches. There is a mass of fine fibrous roots a short distance below the surface. This species is characteristic of very moist sites in the Douglas fir zone but may sometimes occupy similar sites in the permanent brush zone.

### Generalized Spreading Systems

The third class of root systems contains those of the following plants: White fir, western yellow pine (fig. 34, *B*), pointleaf man-

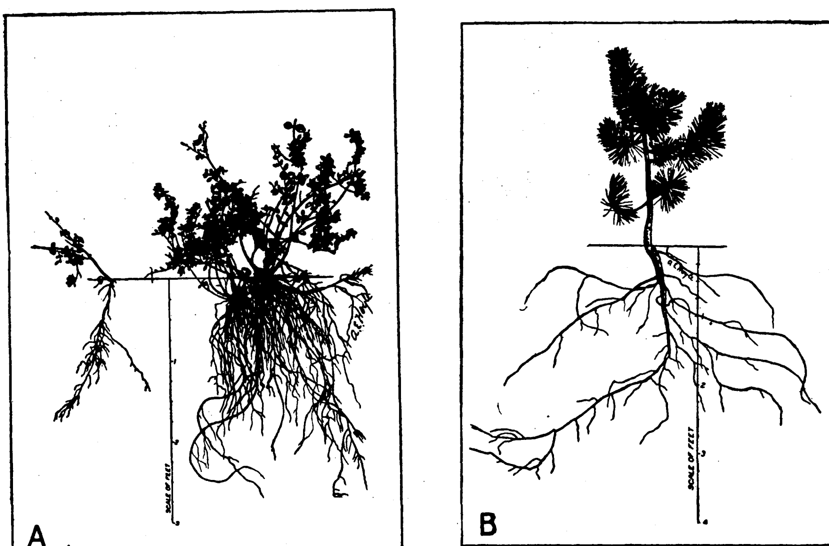



FIGURE 34.—A, Mountain snowberry (*Symphoricarpos oreophilus*) showing development of root system in young and old plants in oak-brush zone; B, western yellow pine (*Pinus scopulorum*) showing development of root system on light sandy soil near the pines station

zanita (fig. 35), mountain snowberry (fig. 34, *A*), snowbrush (fig. 36), russet buffaloberry (*Lepargyrea canadensis*) (fig. 37), and clematis (*Clematis ligusticifolia*) (fig. 38). A generalized root system is characteristic of all these species. Feeding roots are found in both the upper and lower soil layers, so that the moisture of the upper strata is very largely depleted by the activities of these plants. The white fir and western yellow pine are very similar in general form of root system. In both species a taproot is first formed. This later develops into a generalized spreading root system, which draws moisture from successively lower layers as the tree becomes older. There is generally some absorption from relatively shallow soil layers, particularly in white fir. In western yellow pine, however, most of the absorption occurs at depths greater than 2 feet. Surface roots are largely absent from the western yellow pine studied on the Wasatch Plateau in Utah. This may be due to the light summer rains.

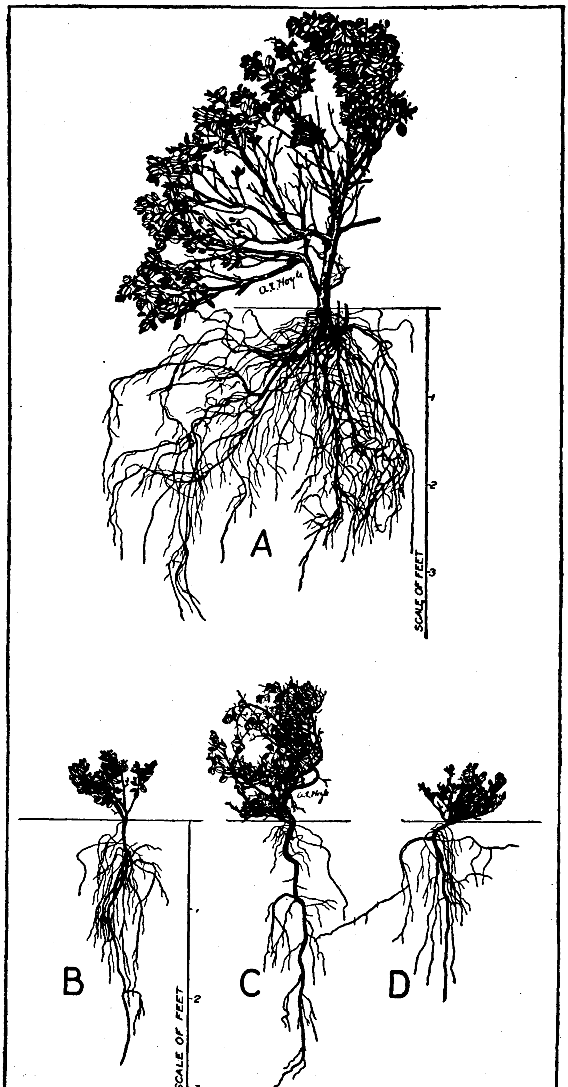



FIGURE 35.—Pointleaf manzanita (*Arctostaphylos pungens*) showing typical root development (A) in calcareous very fine sandy loam on Ephraim Canyon watershed and (B, C, D) in light sandy soil near the pines station

Pointleaf manzanita is distinctly generalized in its root system, and numerous roots spread from the base of the plant in all directions. Some of these roots are large and extend considerable distances before developing feeders, but there are always so many small feeding roots mingled with them that moisture is drawn from a large volume of soil, much of it near the surface and usually close to the base of the plant. This species is not very significant as an indicator. It is most commonly found on severe sites, but because it usually occurs in open stands it does not reduce the soil moisture as much as the root system would indicate.

Snowberry also has a distinctly generalized root system. A few roots extend from the base of the plant in various directions at a depth of only a few inches below the surface of the soil. At distances of a few inches to about a foot, they curve downward and run almost vertically until, at a depth of about 2 feet, they divide into feeding roots which extend to considerable depths. Besides these prominent roots, many small feeding roots extend into the surface layers of soil near the base of the plant.

The soil within a radius of 2 feet of the plant has the upper foot fairly well filled with absorbing rootlets. This species is a common associate of oak brush, serviceberry, chokecherry, and many other plants with deep-feeding root systems and does much to render unsuitable otherwise excellent sites. When well developed it is a very serious competitor of western yellow pine.

Snowbrush has an extensive root system spreading outward and downward. A 3-year-old plant growing in good soil in the Cottonwood nursery on the Wasatch National Forest was found to have lateral feeders all along the main roots to a depth of 26 inches. An older specimen from the adjacent slope had the same general character of root system, except that it extended to depths of 6 to 8 feet.

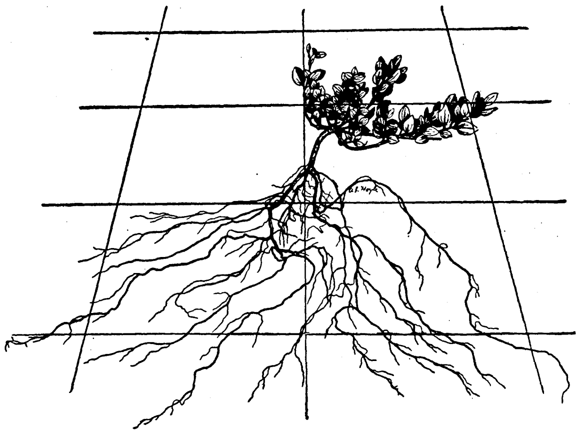


FIGURE 36.—Typical 3-year-old plant of snowbrush (*Ceanothus velutinus*). (12-inch squares in perspective)

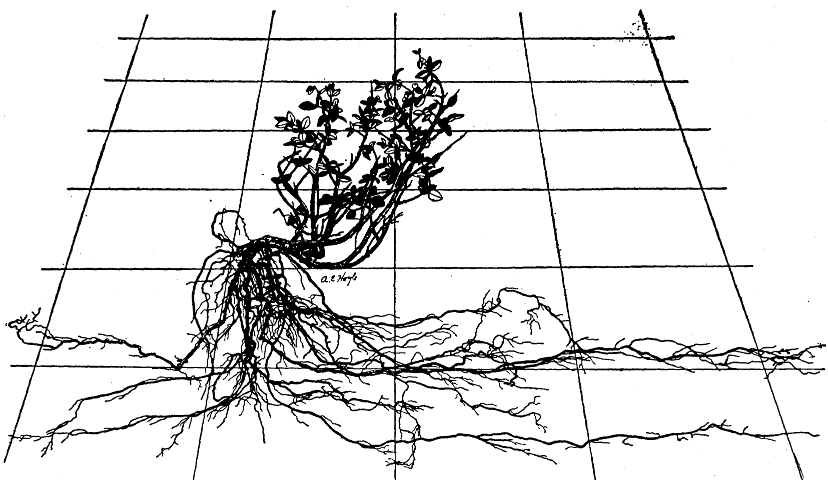


FIGURE 37.—Root system of russet buffaloberry (*Lepargyrea canadensis*). (12-inch squares in perspective)

Russet buffaloberry has a compact, bunched root system with very little tendency to develop a taproot. The root systems studied extended down about 3 feet, but the greater part of the absorbing surface was situated in the upper 18 to 24 inches of soil. The lateral extension amounted to 18 to 24 inches.

Clematis has a rhizome running through the upper 12 inches of soil, but the absorbing rootlets are shallow and closely massed below the plant. The absorbing surface of the roots and rootlets is almost wholly in the upper 12 to 18 inches of soil.

In Utah, the last three species are more characteristic of the temporary brush type of the Douglas fir zone than of the permanent brush lands, and since they occur on more moist areas, the shallow roots are less injurious to conifer transplants than if they were in drier situations. However, snowbrush occurs on more severe sites in central Idaho, in association with the ponderosa form of western yellow pine. Snowbrush has the least superficial root system of all three species. Both russet buffaloberry and clematis are charac-

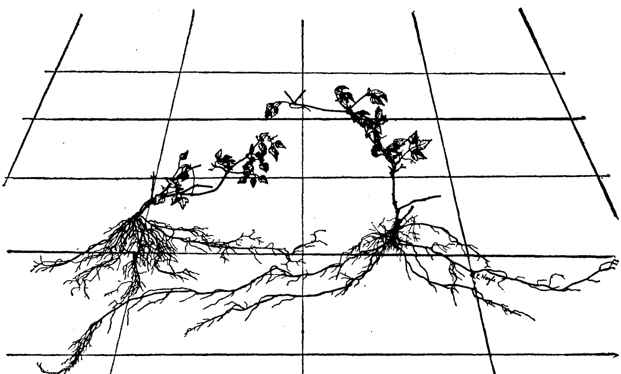


FIGURE 38.—Typical root systems of clematis (*Clematis ligusticifolia*). (12-inch squares in perspective)

teristic of cool, moist sites not often considered as planting sites for western yellow pine.

## TWO-STORIED SYSTEMS

To the fourth class of root systems belong those of sagebrush (fig. 39) and Fendler soapbloom (fig. 40). Of these the sagebrush presents a much more typical 2-storied root system than the Fendler soapbloom. The prominent sagebrush taproot sends out great numbers of small feeding rootlets, longer near the surface and successively shorter, until at a depth of about 2 feet they almost completely disappear. Below this the taproot soon divides, but without developing feeding rootlets until great depths are reached. It is very difficult to locate the final feeding rootlets of the sagebrush on account of their brittleness and the great depths to which they penetrate.

Fendler soapbloom has a root system similar to that of the sagebrush. It has a number of very shallow rootlets extending out from the base of the plant. The taproot extends downward only about a foot before branching and rapidly produces small feeding rootlets. A surface feeding system is developed, as in sagebrush, but the secondary deep-feeding system lies in much shallower soil.

This type of root system, on account of the excessive development of surface rootlets, is very effective in exhausting moisture in the upper soil layers and causing failure of plantations on sites occupied by these two species. Sagebrush is the greater offender of the two, because it normally occupies drier sites, forms denser stands, and has a more extensive development of superficial roots.

### Comparison of Sites

In general, when plants are considered in association, it may be said that those associations occupying the dry ridge tops and south slopes have root systems which feed wholly at great depths. The intermediate classes occupy north slopes and less severe sites, and the shrubs with the best-developed shallow root systems occupy sites which have the best moisture conditions, at least during a part of the growing season. The form of root system varies somewhat within a species and is affected only slightly by soil conditions. Root systems of bitterbrush (fig. 23), manzanita (fig. 35), and sagebrush (fig. 39) from the light sandy soils of the pines station show the same general form as those growing on the heavy clay soils of Ephraim Canyon.

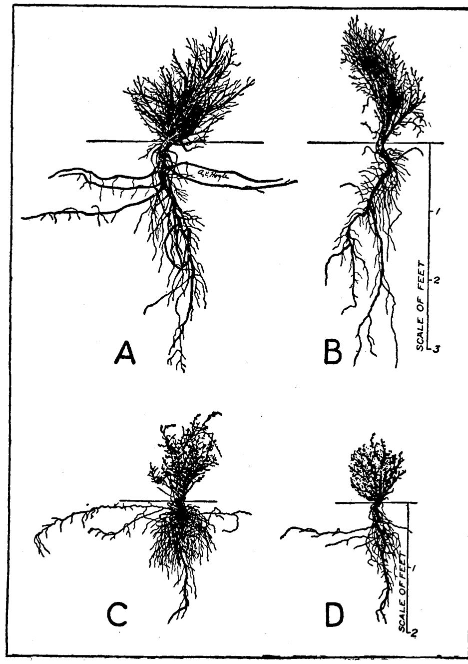


FIGURE 39.—Sagebrush (*Artemisia tridentata*) showing development of root system (A) in heavy clay soil on the Ephraim Canyon watershed and (B) in light sandy soil near the pines station

The root system of any plant will naturally vary somewhat with the moisture conditions under which it grows. A plant will de-

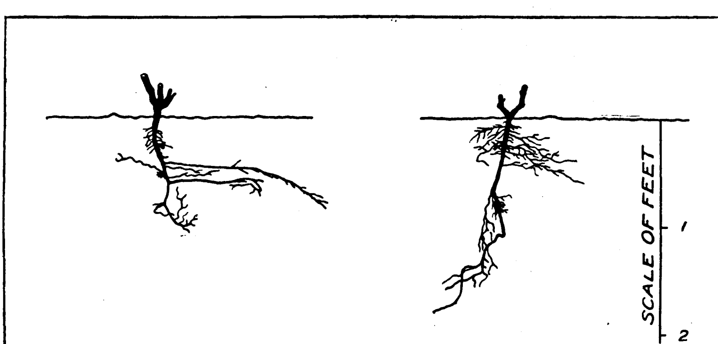


FIGURE 40.—Typical root systems of Fendler soapbloom (*Ceanothus fendleri*) in oakbrush zone

velop but few roots in a horizon which is habitually dry. On the other hand, if the topsoil layer on any site is reasonably moist some plant will take advantage of the available water. It follows then that a predominance of characteristically deep-rooted plants indicates a site on which the upper layers of soil are naturally dry because of deficient rainfall, rapid percolation, or high evaporation. In a year of favorable moisture, planting should succeed, but the planted trees would probably suffer before their roots reached permanent moisture.

After deep-rooted plants become established on a site having a dry surface soil, conditions should gradually improve through the accumulation of a surface mulch and the formation of a humus layer; and, as has already been shown, shade should aid perceptibly in the initial establishment of planted stock. After a site has been improved in this way by deep-rooted pioneers, the native vegetation will be likely to take advantage of the increased moisture in the upper soil layers. The original plants may develop lateral absorbing roots near the surface or may give way to other shallow-rooted species that require surface moisture.

Trees planted on such sites are not likely to make rapid growth unless soil conditions are such that they can develop active absorbing roots fairly near the surface where the organic matter occurs and where the soil aeration, already shown to be necessary, is best. These relations are strongly reflected in the superior height growth of western yellow pine planted on the sagebrush sites. (Table 7.)

The results of planting on sites occupied by the various shrubs common to the brush lands show very conclusively that the soil layers occupied by the absorbing roots become extremely dry—much drier than soil containing no roots at the same depth. That is, the presence of shallow-rooted species feeding near the surface indicates that the trees must be placed in direct competition with the native vegetation and that the site is therefore unsuitable for planting. The best results can be obtained with plantations on sites where absorbing roots of the native vegetation are found at depths below 2 feet and where the trees can safely be placed close to the north side of the bushes where the shade will serve to reduce evaporation and transpiration. Such sites are likely to be naturally severe, as deep-feeding shrubs tend to occupy dry sites. Therefore, in most cases such sites should be selected for forest plantations only when they are otherwise naturally suitable.

If the native vegetation can be removed before planting, sites which originally supported a vegetation composed of shallow-rooted species will prove the most satisfactory, since the presence of such plants indicates that relatively large amounts of soil moisture exist in the upper soil layers during the growing season. This, of course, applies to long-lived annuals or perennials and not to the ephemeral shallow-rooted vegetation that springs up after rains on the deserts.

## LEAF CHARACTERS AS AN INDICATION OF SOIL MOISTURE

It has already been shown that a careful observation of the prevailing vegetation as to root development will facilitate the selection of favorable planting sites. Areas made unsuitable by shallow-rooted vegetation may thus be avoided. At the same time deep-rooted vegetation itself clearly does not guarantee a favorable degree of soil moisture. The site may be naturally dry or well watered. The moist site is of course the better. In general, the vegetation occupying the moist site has leaf characteristics indicating that the plants use water liberally and that the water is plentifully supplied by the roots. A study of leaf characters, including size, structure, moisture content, relative transpiration, and sap density, was made, with the purpose of extending the usefulness of native plants as indicators by showing which deep-rooted species, as heavy users of water, may indicate areas where there is plenty of available water for western yellow pine. The particulars are summarized in Table 14.

TABLE 14.—*Average size, water content, relative transpiration indices, and sap density of representative leaves of species common in the oak-brush belt on the Ephraim Canyon watershed, 1918*

| Species and aspect | Mean area of leaf | Water content of leaf on basis of dry weight | Time of transpiration test | | Transpiration index [1] | Maximum osmotic pressure of sap [2] |
|---|---|---|---|---|---|---|
| | | | Day | Hour | | |
| | *Sq. mm.* | *Per cent* | | | | *Atmospheres* |
| Rocky Mountain white oak: | | | | | | |
| Northern | 4,293 | 133.4 | Sept. 9 | 10.00 a. m. | 0.844 | 20.1 |
| Western | 2,740 | 124.6 | Sept. 12 | 10.00 a. m. | .470 | -------- |
| Southern | 1,267 | 109.8 | Sept. 9 | 3.00 p. m. | .366 | 20.7 |
| Mountain snowberry: | | | | | | |
| Northern | 566 | 159.1 | do | 11.50 a. m. | .794 | 24.3 |
| Western | 308 | 158.5 | Sept. 7 | 10.30 a. m. | .550 | -------- |
| Southern | 97 | 95.2 | Sept. 9 | 4.40 p. m. | .103 | 27.3 |
| Black chokecherry: | | | | | | |
| Northern | 1,995 | 210.0 | do | 11.40 a. m. | .378 | 18.0 |
| Western | -------- | 201.8 | Sept. 7 | 3.30 p. m. | .332 | -------- |
| Fendler rose: | | | | | | |
| Northern | 339 | 150.8 | Sept. 9 | 10.30 a m. | .363 | 17.2 |
| Western | -------- | -------- | Sept. 7 | 3.30 p. m. | .312 | -------- |
| Common serviceberry: | | | | | | |
| Northern | 685 | 150.3 | Sept. 9 | 1.00 p. m. | .558 | 19.0 |
| Western | 544 | 122.4 | Sept. 7 | 3.00 p. m. | .320 | -------- |
| Southern | 294 | 96.9 | Sept. 9 | 3.30 p. m. | .110 | 22.7 |
| Bigtooth maple: | | | | | | |
| Northern | 2,966 | 137.1 | do | 11.00 a. m. | .280 | 16.6 |
| Hollygrape: | | | | | | |
| Northern | 868 | 129.1 | do | 11.30 a. m. | .319 | 16.7 |
| Western | 694 | 128.1 | Sept. 7 | 2.00 p. m. | .310 | -------- |
| Southern | 374 | 114.4 | Sept. 9 | 1.50 p. m. | .100 | 20.8 |
| Birchleaf mountain-mahogany: | | | | | | |
| Southern | 345 | 99.1 | do | 1.20 p. m. | .233 | 15.8 |
| Bitterbrush: | | | | | | |
| Western | 62 | 130.6 | Sept. 7 | 10.30 a. m. | .306 | -------- |
| Southern | 20 | 60.0 | Sept. 9 | 5.30 p. m. | .097 | 16.7 |
| Myrtle boxleaf: | | | | | | |
| Northern | -------- | -------- | Sept. 12 | 2.50 p. m. | .277 | -------- |
| Southern | 45 | 110.0 | Sept. 9 | 3.50 p. m. | .100 | 13.6 |
| Fendler soapbloom: | | | | | | |
| Southern | 163 | 114.6 | do | 4.20 p. m. | .183 | 17.8 |
| Squaw-apple: | | | | | | |
| Southern | 118 | 69.7 | do | 2.10 p. m. | .140 | 25.0 |
| Manzanita: | | | | | | |
| Southern | 934 | 96.6 | do | 1.30 p. m. | .104 | 18.0 |
| Common sagebrush: | | | | | | |
| Western | 89 | 174.2 | Sept. 7 | 10.30 a. m. | .054 | 16.6 |
| Southern | 26 | 79.8 | Sept. 9 | 2.40 p. m. | .038 | 20.2 |
| Winter fat: | | | | | | |
| Southern | 17 | 50.8 | do | 5.00 p. m. | .042 | 20.7 |
| Douglas fir: | | | | | | |
| Northern | [3] 33 | 119.1 | -------- | -------- | -------- | 19.8 |
| White fir: | | | | | | |
| Northern | [3] 100 | 139.8 | -------- | -------- | -------- | 18.6 |
| Western | [3] 60 | 129.8 | -------- | -------- | -------- | -------- |
| Piñon: | | | | | | |
| Southern | [3] 61 | 114.6 | -------- | -------- | -------- | 20.4 |

[1] Based on an average of 16 tests for each species on each site. The determination and use of this index are explained on page 74.

[2] From Korstian (*28*).

[3] The areas of conifer leaves were determined by the formula: $A=L(\pi R+2R)$, in which $L$=length and $R$=half the average diameter of leaf.

### SIZE

It is a common observation that, among the various adjustments of the plant to its environment, a reduction in leaf size often takes place on those sites adverse to plant growth.

The average size of leaf of a number of species native to the three most important aspects in the Ephraim Canyon oak brush were determined.[11] The largest leaves are found on the northern aspect, the smallest on the southern, and the intermediate ones on the western aspect, on which environmental conditions are neither so favorable to plant growth as on the northern aspect nor so unfavorable as on the southern aspect.

The climatic factors of the environment can therefore be interpreted in terms of leaf size, at least to the extent that leaf size varies inversely with the severity of the site. The study of leaf structure considered in the following section emphasizes another phase of leaf reaction to environmental factors.

### STRUCTURE

The structure, as well as the external form, of most plants varies with the site and even with the fluctuating environmental factors of the same site. Some of the most pronounced structural modifications are those of the leaf. As the principal seat of water loss or transpiration, it shows significant differences in the position and development of the palisade and sponge tissues, which are directly traceable to the light and water relations of the plant.

Clements (*14*), in studying about 300 species, found a very pronounced correlation between leaf structure and such physical factors as the moisture content of the soil, light, humidity, and temperature in the Colorado foothills and in the vicinity of Pikes Peak in the Rocky Mountains. Hanson (*21*) correlated the structure of leaves from the outside (south periphery) and center of the same tree with light intensity, evaporation, air temperature, humidity, wind velocity, and the transpiration of excised twigs in the same positions. He found that the differences in thickness between leaves on the south side and the center of the same tree are usually greater than the average differences heretofore reported for the leaves of moist and dry site forms of the same species. The leaves from the south side were found to have more palisade tissue, a more compact structure, and thicker epidermis and cuticle than the leaves from within the crown. The water content of the leaves from the center of the tree was always higher than that of the leaves from the periphery.

Sampson and Allen (*45*) have shown that leaves grown in the full sunlight transpired from two to four times as much as the leaves of the same species grown in the shade, whether placed in the sun or shade. They explained this largely on the basis of the greater number (20 to 60 per cent) of stomata in the leaf grown in full sunlight.

In the present investigation a limited study was made of leaf structure on the opposite northern and southern aspects in the brush belt at an elevation of 7,500 feet on the Ephraim Canyon and Big Cotton-

[11] The reader may be interested to review Raunkiaer's (*19*) system of leaf-area classes in this connection.

wood Canyon watersheds. As far as possible mature leaves were collected from typical species at or near the period of maximum development. The leaves were at once plunged into a killing solu-

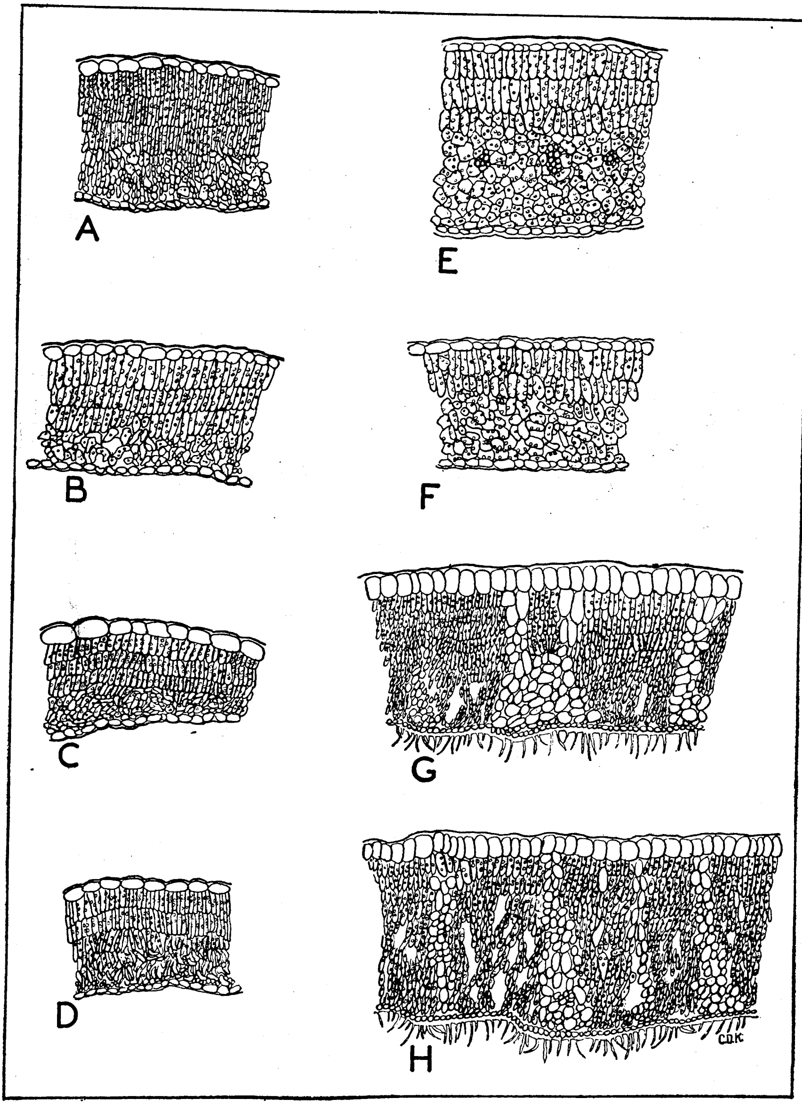



FIGURE 41.—Cross sections of oak brush, serviceberry, hollygrape, and snowbrush leaves grown on southern and northern aspects: A, Oak brush, southern aspect; B, oak brush, northern aspect; C, serviceberry, southern aspect; D, serviceberry, northern aspect; E, hollygrape, southern aspect; F, hollygrape, northern aspect; G, snowbrush on Big Cottonwood watershed, southern aspect; and H, snowbrush on Big Cottonwood watershed, northern aspect

tion and kept there until they were sectioned. Permanent microscopic mounts were made by the paraffin process. Camera lucida drawings were made of the most typical parts of these sections to facilitate subsequent detailed study. (Figs. 41 and 42.)

The results of this study of leaf structure show that the leaves of the species common on the southern aspects are not only smaller and more compact but also that they have a more highly cutinized and thicker epidermal wall, more palisade tissue, less sponge tissue, and more closely crowded stomata than those on the northern aspects.

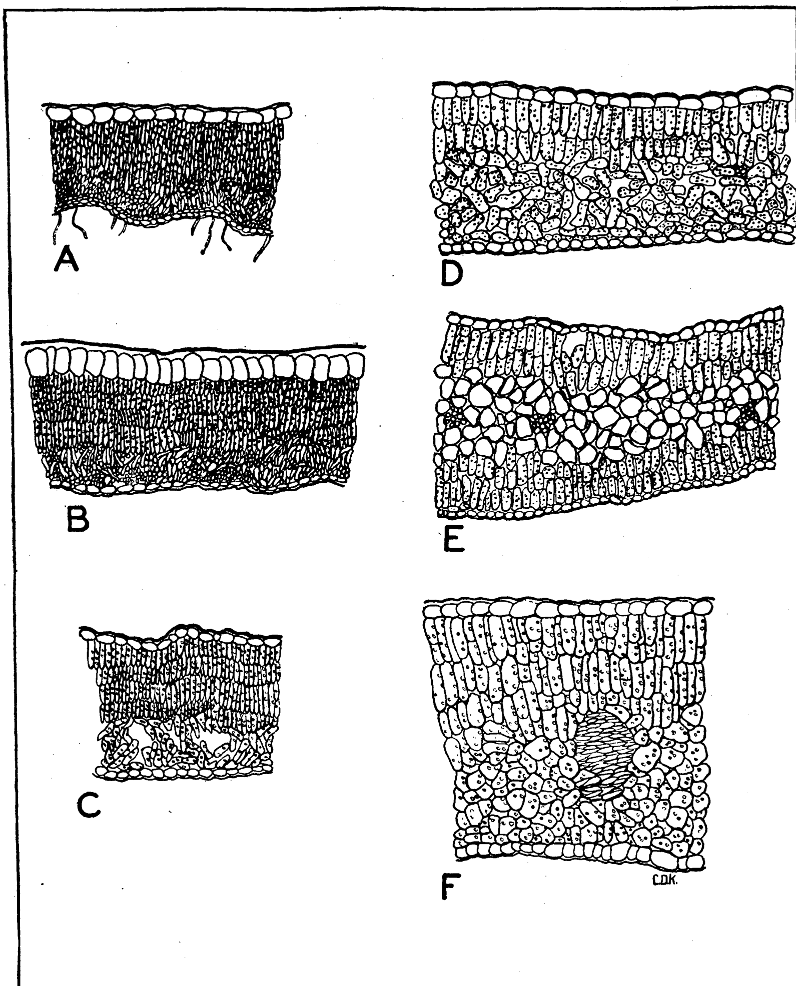
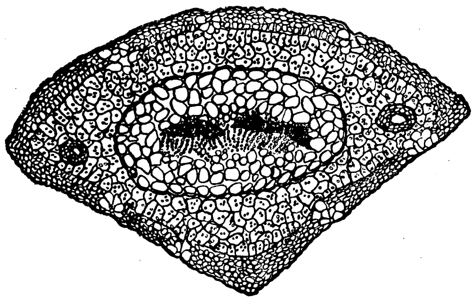


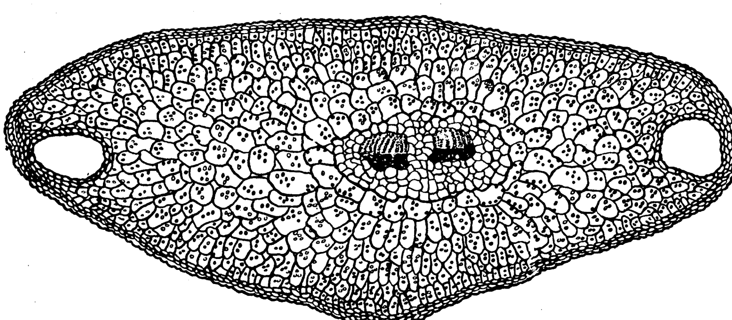

FIGURE 42.—Cross sections of leaves of southern-aspect shrubs: A, Common mountain-mahogany; B, curl-leaf mountain-mahogany; C, mountain snowberry; D, myrtle boxleaf; E, big sagebrush; and F, Fendler soapbloom

Most of these adaptations tend to reduce transpiration and enable the plant to exist on smaller water supplies.

The western yellow pine leaf (fig. 43) also has a structure similar in many respects to that of the brush-land shrubs but possibly of a somewhat less xerophytic type. On the other hand it has a more highly cutinized and thicker epidermis and much more pronounced and thicker palisade tissue than are usually found in the firs and spruces. Most of these characteristics of western yellow pine leaf structure tend to reduce water loss. Although it has already been shown that this species may reduce transpiration in times of water stress and that it competes successfully with the native vegetation in the western yellow pine type, it is naturally handicapped in competing with xerophytes at the lower limit or entirely below its limit of



A



B

FIGURE 43.—Cross sections of (A) western yellow pine (*Pinus scopulorum* form) and (B) white fir leaves from scattered trees occurring on similar sites in the brush-land belt

moisture conditions. These considerations suggest studies of the water relations of the leaves, especially of the brush-land species.

### MOISTURE CONTENT

The variation in the water content of the leaves should throw some light on the relative ability of plants to absorb water from the soil and to transport it to the leaf. To determine this variation, the relative moisture contents of the leaves of the various species in the Ephraim Canyon oak-brush zone were obtained. These are summarized in Table 14. All the leaf samples were collected under similar conditions and as nearly as possible at the same time, since, as shown by Livingston and Brown (*34*) and by Clark (*13*), a general increase in water content occurs by night and a general decrease by day, and on dry sites the water content is greater during cloudy than clear weather. Water content, like leaf size, indicates that slopes having a southern aspect constitute the most adverse sites. The highest moisture content is found in leaves on north slopes. The water content of leaves on western aspects occupies an intermediate position.

It is evident from Table 14 not only that a definite relation exists between site and moisture content of the leaf but also that the relative rate of water intake and water loss in different plants on the same site and in the same plants on different sites is involved.

### RELATIVE TRANSPIRATION

The relative transpiration of the leaves of plants—their relative capacity for giving off moisture to the surrounding air—is often an important factor in studies of the water relations of plants on semiarid sites. Transpiration, furthermore, portrays a summation of the conditions within the leaf which affect water loss.

Following Livingston's (*32*) suggestion that the capacity of a plant to lose water is an index of its ability to resist water loss, the mean indices of the relative transpiration of representative leaves were determined for the shrubs common in the oak-brush belt of central Utah. Average indices based on 16 tests[12] for each species on southern, western, and northern aspects at an elevation of 7,500 feet in Ephraim Canyon are given in Table 14.

Following the suggestion of Bakke (*4*) that all plants with indices below 0.30 be considered xerophytes (drought-resistant plants) and all with indices above 0.70 mesophytes (moisture-loving plants), it will be seen that most of the species in Table 14, especially winter fat, big sagebrush, pointleaf manzanita, squaw-apple, Fendler soapbloom, and common mountain-mahogany are typical drought-resistant plants. Some of the species, especially those near the top of the table, lie in the intermediate group. From these tests, therefore, it may be concluded that the relative transpiration of leaves provides a criterion by which the relative drought resistance of plants may be compared. Furthermore, by the same criterion, many of the shrubby species of the brush lands are typically adapted to withstand drought conditions of probably greater intensity than those which western yellow pine can withstand.

### SAP DENSITY

Another means of interpreting the water relations of the site through the characteristics of the native vegetation is by the density of cell sap in the leaves. When two solutions are separated by a semipermeable membrane—such as a cell wall—a constant flow of

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[12] In these tests, made September 7 to 12, 1918, essentially the same method was used as that described by Livingston. Small slips of thin filter paper, impregnated with cobalt chloride, were dried for a few seconds over a thin metal plate, heated by an alcohol lamp, and immediately applied by means of glass clips to the surface of the leaf to be tested. The time required for the change in color (from blue to pink) was determined with a stop watch. The quotient of the time required for the color change over the standard evaporating surface at the same air temperature, divided by the time required for the color change on the leaf, is the index of relative transpiration of the leaf surface. This index expresses the relative capacity of the leaf surface to give off water vapor as compared with a standard evaporating surface blanketed by a millimeter of air.

water passes from the weaker to the denser solution until they attain an equilibrium. While there are other contributing forces, this force or osmotic pressure, in conjunction with the tensile strength of water, is considered by the writers to be the chief means by which the supply of water and solutes constantly being absorbed from the soil by the root hairs of all green land plants is passed upward through the plant to the leaves to be given off into the air as water vapor. An indispensable stream is thus maintained chiefly through the osmotic properties of the cell sap of the leaves, which may be regarded as developing the suction force necessary to absorb the moisture from the soil and to lift it up through the roots and stems to the leaf cells. The leaf, by maintaining a cell sap which is more concentrated than the soil solution, insures a constant stream of water and solutes passing up to it. This stream never succeeds in greatly diluting the cell sap in the leaves because the moisture brought up from the soil constantly diffuses into the air. The large number of plant cells involved and the substances in solution complicate the absorption of water and its passage through the plant, but although millions of cells may intervene a direct osmotic gradient exists between the topmost leaf of the tallest tree and the soil solution at its root tips.

The measure of osmotic pressure is thus somewhat of a measure of the plant's ability to overcome those most significant of environmental factors—the forces with which the soil withholds and the air withdraws water from the plant. When moisture is plentiful in the soil, as in the spring or after heavy rains, the force required to pull it up to the leaves is not great, and accordingly a relatively dilute cell sap is sufficient to maintain the stream. With the advent of summer and the drying out of the soil, the leaves must exert a progressively greater pull to obtain the requisite amount of moisture from the soil; the cell sap becomes more concentrated and therefore the osmotic pressure increases.

The concentration of the cell sap in the leaves does not depend entirely upon soil moisture, however, for under the same soil conditions concentration is higher in woody plants than in herbs and higher in trees than in shrubs. Apparently greater force is required to draw the moisture up through long woody stems than through short succulent tissues. The concentration also varies with the time of day and with the weather; a hot, dry day may bring about such rapid transpiration that a notable increase in sap concentration occurs before the moisture lost from the leaves can be replaced. In spite of all these minor variations, sap density is a convenient measure of the difficulty encountered by the plant in obtaining moisture from the soil. In the critical period of midsummer this factor becomes an excellent measure of the severity of the site, especially in terms of the soil moisture at the level of the absorbing roots. The leaf-sap concentration can not increase indefinitely in response to drying of the soil, for every plant has a limit beyond which the sap concentration can not go. If this point is passed the plant wilts and dies from plasmolysis. Therefore the maximum osmotic pressures observed in the hot, dry part of the summer enable the grouping of plants in the order of their ability to withstand dryness.

Sap density in relation to environmental conditions in this region has been made the subject of a special study by Korstian (*28*), and only the material pertinent to the present study will be repeated here. Table 14 gives osmotic pressures for a number of species during the latter part of July. Planted western yellow pine on the same sites showed an osmotic pressure varying from 19.8 atmospheres in the ponderosa form to 23 atmospheres in the scopulorum form at the same time. On the basis of these figures, western yellow pine appears physiologically able to extract water from soils almost as dry as most of those typical of the brush lands. However, this species planted on south-facing slopes in the brush belt often has lower sap concentrations than many of the more common shrubs native to these sites. This suggests that the range in sap concentration of western yellow pine is after all lower than that of the brush-land species. Moreover, planted western yellow pine has a deficient root system the first year, due to transplanting; and though the sap concentration may rise very high, the plant is not always able to absorb water fast enough through the few living rootlets. Accordingly, it may wilt and die in a fairly moist soil. With a less extensive root system than a neighboring shrub, pine may yet exhaust the available soil moisture immediately around its rootlets much faster than does the shrub.

Sap density alone, therefore, may not invariably indicate the behavior of a species planted on a given site under conditions of extreme dryness, but taken in connection with other factors it aids greatly in the interpretation of site quality in terms of the native vegetation. The study of sap density shows that it is unwise to plant a species on any site the native vegetation of which possesses uniformly higher sap densities than those generally maintained by this species during the dry season.

## RELATIVE SIGNIFICANCE OF LEAF CHARACTERS

It is obvious from the preceding discussion of leaf characters that large, thin leaves having a high water content and high rate of transpiration coupled with a low osmotic pressure indicate favorable moisture conditions, whereas the opposite factors denote unfavorable moisture conditions. The vegetation rarely shows a uniform correlation of all these characters with site. For example, snowberry on north slopes has relatively large leaves, a high moisture content, and a high rate of transpiration. The osmotic pressure, however, is notably high. On the other hand, manzanita has the contradictory factors of large leaves, low osmotic pressure, low moisture content, and a low transpiration rate. There is no satisfactory way of summarizing all these factors so that their resultant effect is evident, for their relative importance is still largely unknown. If, however, the values given in the various columns of Table 14 are divided into three equal groups—high, medium, and low—and arbitrary numerical values, 1, 2, and 3, are assigned to them, a rough summation of the four factors—leaf area, water content, transpiration rate, and sap density—shown in Table 14 can be obtained.

On this basis the species fall in the following order, progressing from those indicating the best moisture conditions to those indicating the poorest. Species under the same number have equal standing, and the letters N, S, and W indicate north, south, and west aspect.

(1) Black chokecherry (N); mountain snowberry (N).

(2) Rocky Mountain white oak (N); Fendler rose (N); creeping hollygrape (N).

(3) Rocky Mountain white oak (S); common serviceberry (N); bigtooth maple (N); big sagebrush (W).

(4) Creeping hollygrape (S); common mountain-mahogany (S); myrtle boxleaf (S); Fendler soapbloom (S); pointleaf manzanita (S).

(5) Common serviceberry (S).

(6) Bitterbrush (S); big sagebrush (S).

(7) Mountain snowberry (S); squaw-apple (S); winter fat (S).

The relationships indicated by this grouping agree closely with the results of the plantations on sites occupied by these shrubs. The best soil conditions are found on sites occupied by species standing high in the list, although the failure of plantations due to insufficient light is assured under oak-brush, chokecherry, or maple cover. Shallow-rooted species appearing low in the list (snowberry and sagebrush) indicate especially poor sites, for they offer keen root competition at critical times and are also very drought resistant, so that the planted trees have very poor chances of survival. Open oak brush, the north sides of clumps of serviceberry (when the clump is not surrounded by snowberry), and north slopes with scattered low rose bushes appear to be the most favorable planting sites, when all factors, including shade, are considered.

The plants studied do not comprise all the species of the dominant associations in the brush-land belt. Their indicator value is given, therefore, not with the expectation of classifying all the sites in the brush-land region but to show the feasibility of determining the value of the sites for planting by studying the characteristics of the native vegetation growing upon them.

## SUMMARY AND CONCLUSIONS

Western yellow pine, which is otherwise rather generally distributed throughout the western United States, is absent in a belt extending from the Gulf of California northeastward into west-central Montana. In northern Utah and southeastern Idaho, where this belt is several hundred miles wide, the elevations at which the pine is commonly found in other parts of the West are occupied by brush-land shrubs. A comparison of this brush-land belt with the natural pine zone reveals both similarities and differences in climatic and soil conditions. It is among the differences in these conditions that the factors which make the brush lands unsuitable for the germination and early development of the yellow pine seedlings are to be found.

A comparison of conditions in the western yellow pine zones to the north and south with those of the intervening brush lands brings out the following facts.

Although no significant differences in temperature exist and there are no notable differences in total annual precipitation, the distribution of rainfall during the summer months in the brush lands is notably different from that either to the north or the south. In the north, May precipitation within the temperature zone suited to western yellow pine is ample for the reproduction of this species. In the pinelands to the south, the July and August precipitation, which greatly exceeds that in the brush lands, is ample for the reproduction of western yellow pine. In the intervening brush lands the light character and brief duration of May rain, coupled with the extremely dry June that quickly follows, prevents the establishment of the reproduction in the early spring. Deficiencies in July and August precipitation, combined with the fact that the rainfall usually culminated in August shortly before the early autumn frosts occur, make it impossible for the species to reproduce.

The importance of evaporation can not be readily ascertained, owing to insufficient data, although its indirect effect upon soil moisture and transpiration is doubtless important.

The generally calcareous, heavy, fine-grained soils of the brush lands are prevailingly unsuited for western yellow pine. While the distribution of rainfall primarily determines the pineless belt, the details of its boundaries are chiefly the results of local soil differences, the pine spreading far from the main bodies on sandy soils and along streams. Certain areas characterized by heavy, fine-grained soils and a flat topography, as the upper Snake River plains, are without western yellow pine, although rainfall and other climatic factors are favorable.

Variations in the combination of factors which influence soil moisture directly or indirectly, as temperature, soil texture, physiography, and the presence of competing vegetation, also explain many of the causes underlying the failure of the species to develop in the brush lands.

The effectiveness of these climatic factors in preventing the establishment of western yellow pine in the permanent brush lands is confirmed by the failure of many plants most commonly associated with this species to become established there.

The western yellow pine type is the only extensive western forest type which exhibits this characteristic of a range broken by a large and practically blank area near its center. Neither the Douglas fir nor the piñon-juniper type shows any such separation. This might be construed as evidence against the theory that a real barrier exists which divides the western yellow pine type. In the Douglas fir and piñon-juniper types, the continuity of range is easily explained on physical grounds. In the Douglas fir zone the total annual precipitation is greater, snow melting is later (at a warmer season), and the dry period in June is thereby shortened, making conditions notably less unfavorable. Douglas fir can apparently grow on as dry sites as western yellow pine if they do not become too hot. Hence a continuous range is possible in this and the higher zones.

The piñon-juniper type, characteristically below the western yellow pine type, extends through most of the region of the pineless belt nearly to the Utah-Idaho State line, which is its northern limit. Reproduction here is not so much affected by May climatic conditions as by those in April and even earlier, which give a longer early spring wet period than in the oak-brush zone lying above this type. Furthermore, the piñon and juniper are undoubtedly better adapted for germination and development on dry sites.

It is clear that western yellow pine can not naturally invade the permanent brush lands and that there is little possibility of artificial stands reproducing themselves naturally even at maturity. Furthermore, the establishment of artificial stands by planting, though by no means impossible, is rendered difficult by the same rainfall factors that operate so powerfully against the natural reproduction of this species. Success in planting generally occurs only on sites with moisture conditions above the average, and conspicuous success has been attained only in seasons of exceptionally heavy spring rainfall. Suitable sites are not easily selected in average years, for they generally bear such luxuriant brush cover that failure due to shade is almost certain.

It is generally advisable, therefore, either to remove the cover before planting or to select essentially poorer sites with less complete cover. Sites with shallow-rooted vegetation, such as sagebrush, should be avoided, as the root competition involved generally results in failure. Successful planting has been done on areas from which a shallow-rooted vegetation has been removed, as well as in stands of deep-rooted shrubs with light foliage, where the soil is naturally moist and sheltered (north and east exposures). Where the site is not thus sheltered, planting has been somewhat less successful even when the natural shrubby vegetation consists of the deep-rooted species. Least suitable of all are excessively shaded sites or those having a predominantly shallow-rooted vegetation. Survival is primarily determined by soil moisture, and to a lesser extent by soil texture, light soils being most suitable. Losses after the second year are usually the result of too dense shade.

Soil moisture, root competition, and degree of shade must be considered in selecting planting sites. A study of the vegetation on the ground enables all three factors to be evaluated with fair accuracy. The root characters of the vegetation and the leaf characteristics, including size, moisture content, transpiration rate, and sap density at the critical period in midsummer, give an insight into the fundamental water relations of the site, while observations on crown density reveal the intensity of shade. With the aid of these criteria it is possible to select the most suitable sites in the brush lands. A species should not be planted on any site the native vegetation of which possesses uniformly higher sap densities than those generally maintained by this species during the dry season.

The present study has shown that, contrary to an earlier belief, the brush lands are fundamentally unsuited to the natural reproduction of western yellow pine and that its absence is not caused by mere accident or the agency of repeated fires. Moreover, there is no evidence that stands artificially established will maintain themselves or spread naturally as originally expected. The growth of western yellow pine on these sites is slow, and the trees promise to be short, limby, and of poor quality at maturity.

Furthermore, only a portion of the brush lands can be classed as suitable planting sites, and the best sites, covered with deep-rooted, thin-foliaged shrubs on northern exposures, are rare. The next best group of sites—cleared or burned sagebrush areas—may show fair success. The remainder of the sites are inferior.

It is evident, therefore, that extensive planting operations in the permanent brush lands of the intermountain region are not justified.

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